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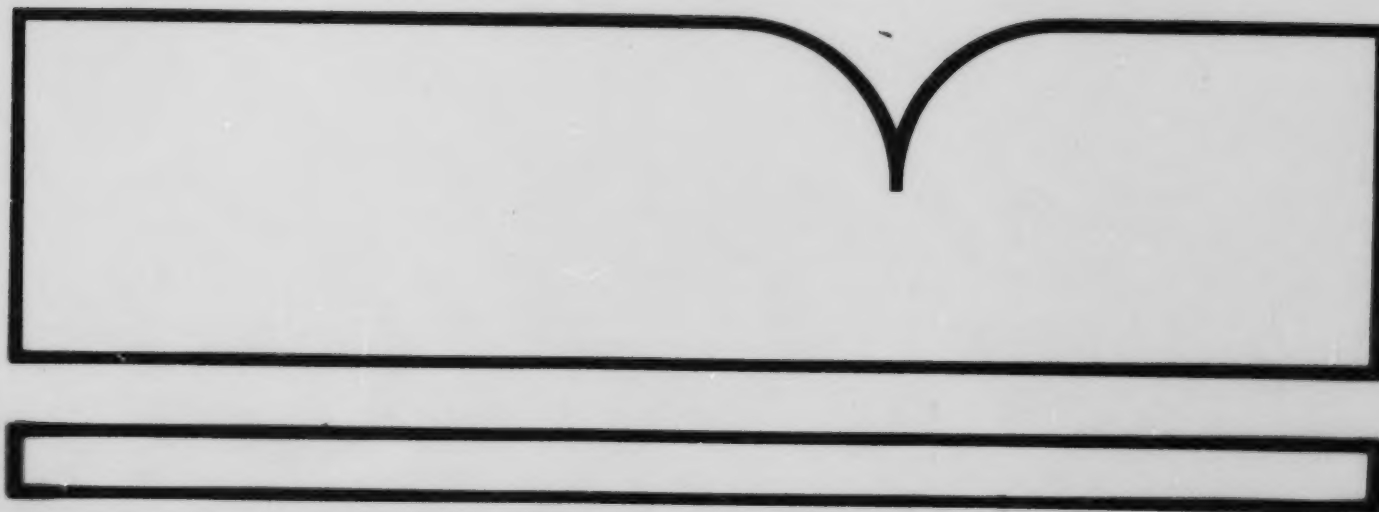
Estimating Costs of Granular Activated
Carbon Treatment for Water and Wastewater

Radian Corp., Austin, TX

Prepared for

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**ESTIMATING COSTS OF
GRANULAR ACTIVATED CARBON TREATMENT
FOR
WATER AND WASTEWATER**

FINAL REPORT

by

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16. ABSTRACT This report discusses design considerations and presents system module costs for conceptual cost estimating of granular activated carbon systems for water and wastewater treatment. It illustrates the development of total system costs using the system module costs. Section 2 of the report describes the background for granular activated carbon use in three application areas: drinking water, municipal wastewater, and industrial wastewater treatment. The relationship of the present work to previous work is discussed; graphs are provided comparing results of this report with previous work. Section 3 covers design considerations for GAC systems. Types of carbon systems are identified and defined in terms of process modules, which are the basis for cost estimates. Design parameters are examined for the three major functional segments of a carbon adsorption system: adsorption, carbon regeneration, and carbon storage and transfer. Section 4 describes process modules and presents modular cost data in terms of direct capital costs and processing expenses. In Section 5, the modular costs are combined and developed into system costs. A "typical" system from each application area is used as an example. A sensitivity analysis example shows how major design variables can affect costs. The user can prepare specific estimates and sensitivity analyses using the procedures illustrated.		
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Foreword

Environmental policy planners, permit writers and reviewers, management and budget officials, and developers of environmental control technologies use cost information to make effective decisions. Reliable, concise, and understandable cost data on capital investment, operating expenses, and revenue requirements serve to reduce the manager's level of uncertainty, and consequently improve his overall performance in attainment of specific environmental policy goals.

To meet the objective of providing reliable, concise, and understandable cost data, EPA's Office of Environmental Engineering and Technology (OEET) presents ESTIMATING COSTS OF GRANULAR ACTIVATED CARBON TREATMENT FOR WATER AND WASTEWATER. This report represents one of EPA's efforts to provide cost information on selected environmental technologies.

It is hoped that, as an estimating guide for costs of granular activated carbon systems, this report will be often and widely used by technical personnel, managers, and planners who need detailed information for estimating costs of these systems.

William A. Cawley, Acting Director
Industrial Environmental Research Laboratory

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SECTION 1

SUMMARY

This report discusses design considerations and presents system module costs for conceptual cost estimating of granular activated carbon systems for water and wastewater treatment. It illustrates the development of total system costs using the system module costs.

Granular activated carbon (GAC) is used to treat drinking water supplies, and municipal and industrial wastewaters. GAC is also used as a treatment technology for contaminated water resulting from previously uncontrolled chemical waste disposal. Interest in granular activated carbon treatment for these applications stems from a need to reduce concentrations of toxic and other objectionable organic compounds harmful to human health and the general environment. GAC can reduce the concentrations of certain organic materials to lower levels (at an acceptable cost) than might be achievable for these materials using other technologies.

As with other environmental control technologies, costs for meeting treatment objectives must be taken into account in policy planning. This is especially true today with more emphasis being placed on cost/benefit analysis as a tool in guiding regulatory policy. In addition, operating facilities subject to regulation also need to evaluate costs. This manual provides a data base for preparing conceptual estimates to aid in policy planning, technology assessment activities, and cost evaluations of facilities.

Section 2 of this report describes the background for granular activated carbon use in three application areas: drinking water, municipal wastewater, and industrial wastewater treatment. The approach for compiling and developing cost data is discussed. The scope and limitations of the report are also defined and a brief review of previously published cost information is provided. The relationship of the present work to previous work is discussed; graphs are provided comparing results of this report with previous work.

Section 3 covers design considerations for GAC systems. Types of carbon systems are identified and defined in terms of process modules. These modules are the basis for the modular costs and system cost estimates presented in later sections of the report. The overall features of granular activated carbon systems are discussed and major design parameters examined for the three major functional segments of a carbon adsorption system: adsorption, carbon regeneration, and carbon storage and transfer. References for Section 3 will provide the reader with more details of design considerations than are

discussed in this report. The purpose of Section 3 is to highlight, not exhaustively analyze, design considerations. The discussion in Section 3 is necessary to ensure proper interpretation and use of the cost data of Sections 4 and 5.

Section 4 contains modular cost data. Direct capital costs and processing expenses, as defined by Items 11 and 70 in a report by Uhl (1), are presented for the process modules that are defined in Section 3. For each process module in Section 4, there is a brief description, a listing of the design basis and assumptions for the cost data presented, a schematic figure of the module where appropriate, and cost graphs.

In Section 5, the modular costs of Section 4 are combined and developed into system costs. A 'typical' system from each application area is used as an example. A sensitivity analysis of one of the systems shows how major design variables can affect costs. The user can prepare his/her own specific estimates and sensitivity analyses using the procedures illustrated by these examples.

Appendices provide miscellaneous technical data and conversion factors.

REFERENCES - SECTION 1

1. Uhl, Vincent, W. A Standard Procedure for Cost Analysis of Pollution Control Operations. Vol. I. User Guide, EPA 600/8-79-018a. Vol. II. Appendices, EPA-600/8-79-018b. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, N.C., June 1979.

SECTION 2

INTRODUCTION

2.1 BACKGROUND

The desire for better water quality and a concern for toxic substances have been the primary motivations for increased use of advanced water treatment technologies. The Office of Environmental Engineering Technology (OEET) has recognized the need for readily accessible cost information on environmental control technologies in order to analyze economic impacts of technology and policy options. This report is intended to present a reliable package of cost information and estimating methods applicable to granular activated carbon (GAC) systems. It is designed to draw attention to design considerations that may have a significant impact on costs.

Activated carbon has been used for many years in both drinking water and wastewater treatment. Activated carbon's ability to remove contaminants from many waters and wastewaters makes this technology attractive for use in achieving high levels of water quality.

Two approaches commonly used for wastewater treatment with activated carbon are:

- construction and operation of an in-place treatment plant at the source, and
- use of a privately-contracted service for carbon absorption.

It is the objective of this cost manual to provide a means of estimating in-place GAC system costs, not costs for contracted services. The only reliable costs for such a service must be obtained from vendors supplying the service.

A great deal of activity has occurred in the GAC area over the last ten to fifteen years. During this period, a large amount of technical data have been generated from laboratory-, pilot plant-, and commercial-scale systems, and the data base continues to grow. Numerous cost and economic studies have also been conducted; some of this information has been published.

This report uses well-documented published cost data to develop specific costs for granular activated carbon technology used in both drinking water and wastewater treatment, and presents these costs in a readily usable format.

The report introduces new cost estimation information for GAC to complement existing data. The report identifies major variables affecting costs and provides a tool for quantitatively assessing their impact on costs of complete GAC systems.

2.2 APPROACH

Granular activated carbon systems are defined in terms of process modules, the major process equipment components or subsystems which comprise the total GAC system. Cost curves are presented for each module. To obtain total system costs the user can combine the costs of appropriate process modules for any GAC system. Examples of total GAC system costs are developed to illustrate the use of the individual module cost concept.

To ensure proper application of the cost data in this report, Section 3 discusses important fundamentals of GAC system design. The user is referred to other literature for more detailed design information. The design information provides the basis for module definition and the modular costs of Section 4, and the support material for the development of the system costs in Section 5. Design considerations provide the user with the insight into many variables that directly influence specific system design, and indirectly, the costs of the system.

2.3 PREVIOUS WORK

The modular approach of this report was used in varying degrees in several previous publications. One of the most comprehensive works was a report in three volumes by Gumerman, et al. (1). The Gumerman report contains costs for major components of GAC systems as well as for other water treatment processes and is a primary reference for the present work. Some costs obtained from the Gumerman report were updated and adjusted to conform to the presentation format in the present work. The present work, however, expands the Gumerman data in order to provide more cost details and permit comparative estimates for a wider variety of design situations. It is a natural evolution in the development of a more comprehensive data base for estimating GAC system costs and carrying out cost and economic analyses for these systems.

Some reasonably detailed cost data are also available in other earlier publications. The Carbon Adsorption Design Manual (2) contains cost curves for several major components of GAC systems. These costs, however, are based on rather limited data specific to the South Tahoe and Orange County projects in California, two of the earliest municipal wastewater GAC facilities.

A limited breakdown of cost data is also given by Rizzo and Shepherd (3) and Zanitsch and Stenzel (4). These costs are provided for adsorption, storage, and regeneration subsystems of GAC systems used for industrial wastewater treatment. Rizzo and Shepherd provide costs for systems up to 1 mgd while Zanitsch and Stenzel extend this range to 10 mgd.

Total costs for several actual systems based on reported project completion costs are presented by Culp et al. (5). Only total costs were available, however. There were no breakdowns by subsystems or system components.

Another limited breakdown of costs for GAC treatment of municipal wastewater is presented in the Innovative and Alternative Technology Manual (6). The costs in the I & A Manual were based on costs appearing in the Petroleum Refinery Point Source Category Development Document (7). These costs were also presented in somewhat modified form in the Treatability Manual (8).

Costs for GAC systems applied to municipal wastewater treatment are also contained in the wastewater treatment cost estimating computer program, CAPDET, used by the Office of Water Program Operations (9).

Other reported costs for GAC systems occur throughout the literature. To the authors' knowledge, the references already cited contain the most comprehensive approaches to presenting GAC costs. Other references may provide costs for specific systems with varying levels of detail. Some references deal primarily with sensitivity analyses of system costs rather than estimation procedures.

An early comparative analysis of activated carbon systems in an industrial wastewater treatment context was published by Cover and Wood (10). This work did not provide detailed costs of modules, but was primarily a sensitivity study of the effects of major variables on total system costs for industrial wastewater treatment. A sensitivity analysis of GAC treatment in the context of drinking water systems was prepared by Clark et al. (11).

2.4 COMPARISONS OF GAC SYSTEM COSTS

Section 5 of this report presents examples of three GAC systems and illustrates how modular costs are combined to develop system costs. The relative contributions of various cost modules and cost elements to system costs for these examples are illustrated in Figures 2-1 through 2-4. These examples are discussed in detail in Section 5. Example 1 is for a drinking water treatment system, example 2 for municipal wastewater treatment, and example 3 for industrial wastewater treatment. All examples are for a 10 mgd design flow rate. The relative contributions of the modules vary between systems, reflecting differences in the individual design requirements for each example. These examples illustrate differences that can occur in systems designed for the same flow rate. However, the relative costs of these three example systems do not necessarily reflect an inherent difference among costs in the three application areas addressed. Also, the relative contributions of various components can change with system size.

A comparison between capital costs developed in the present report and costs from, or developed from, some literature sources is illustrated in Figure 2-5. All costs were updated to a common basis of September, 1980 dollars. Although the present report calculates system costs as total capital

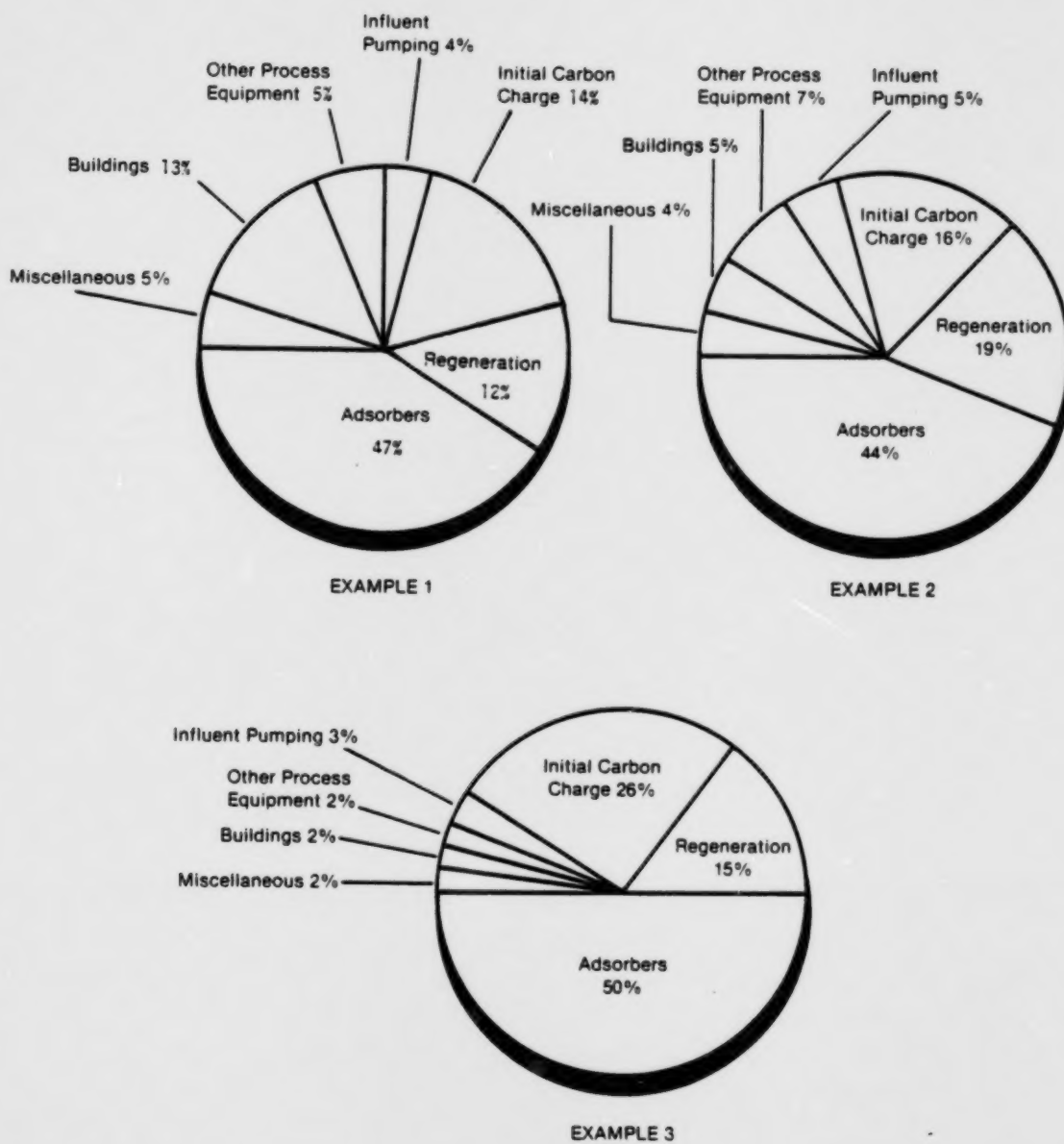


Figure 2-1. Modular cost profile of direct capital cost for three example systems.

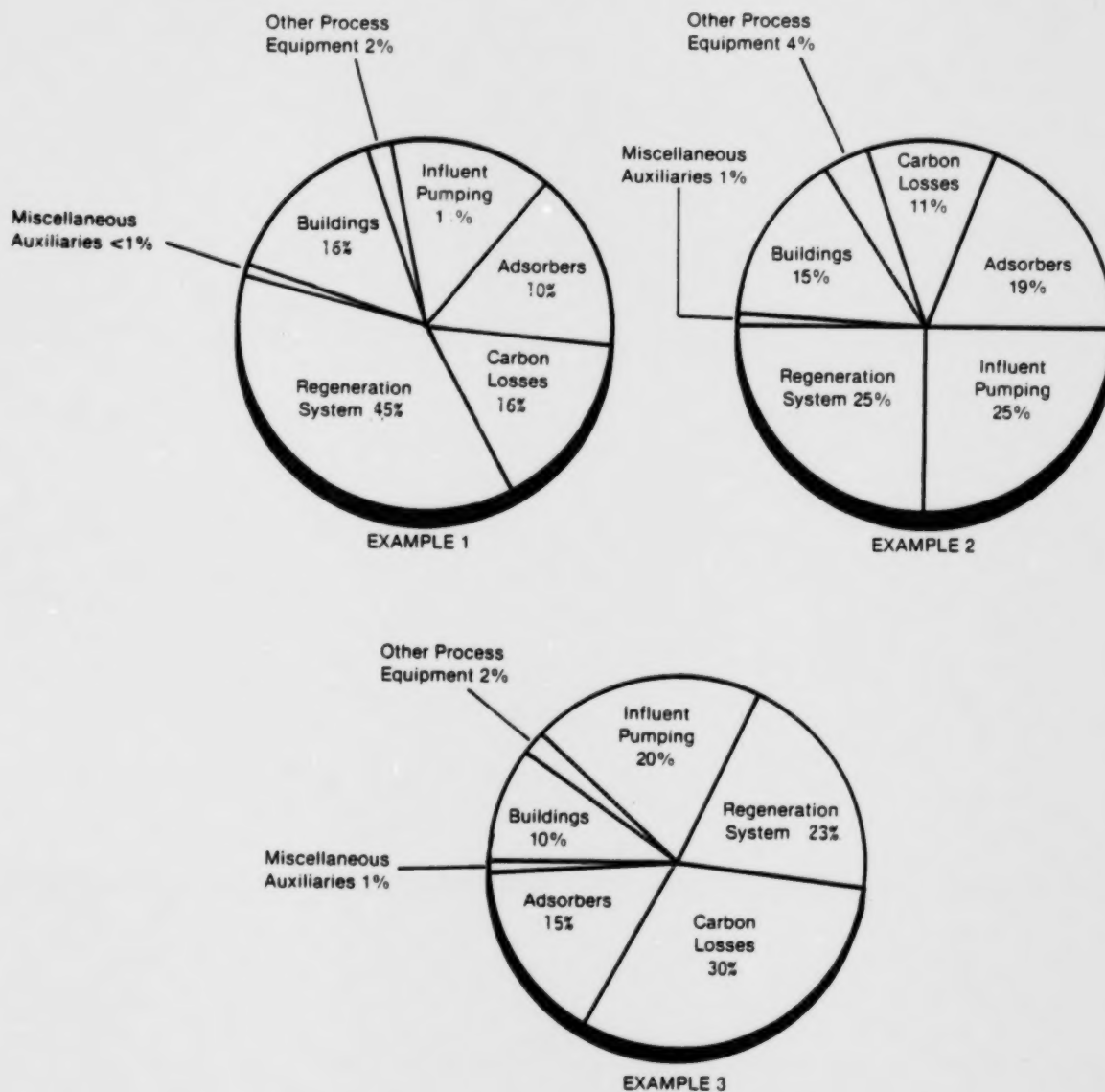


Figure 2-2. Modular cost profile of processing expenses for three example systems.

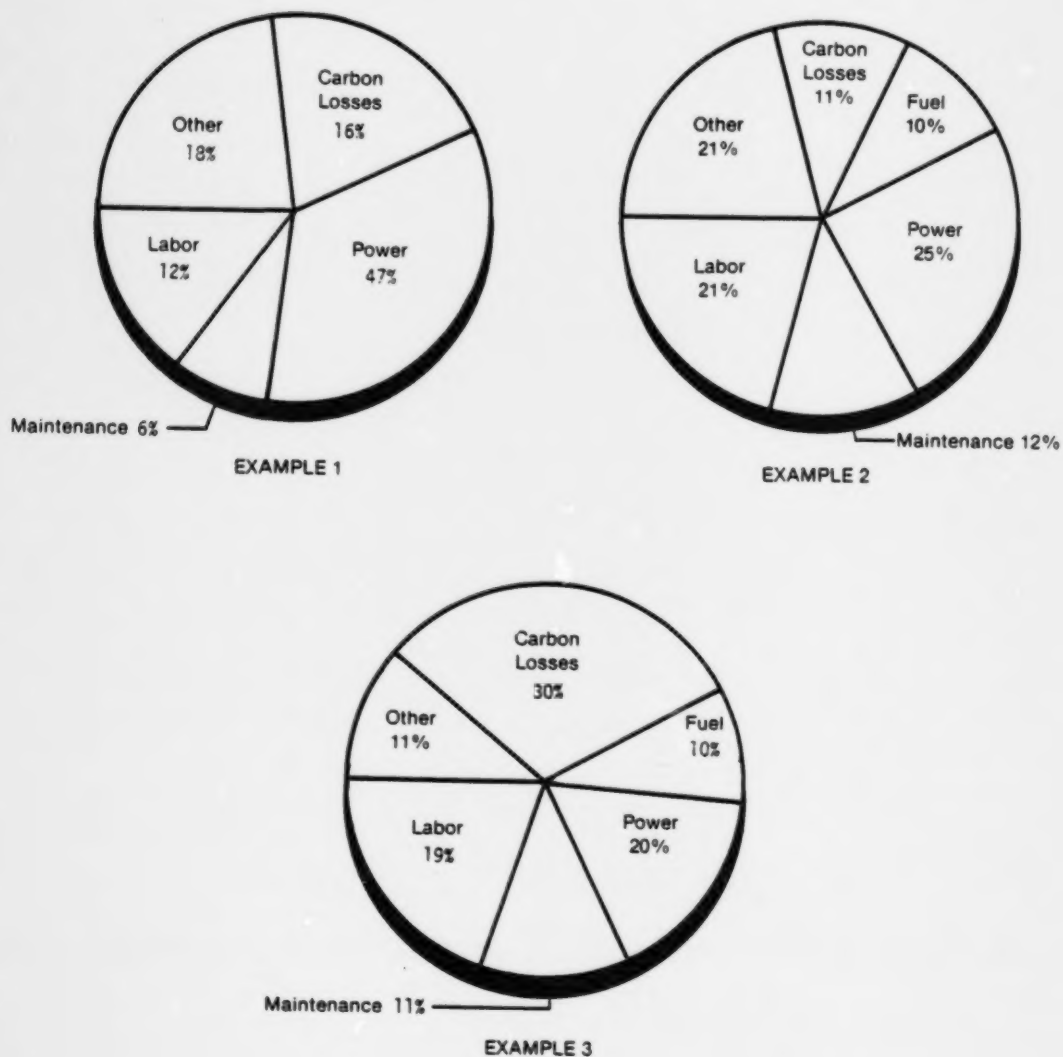


Figure 2-3. Cost element profile of processing expenses for three example systems.

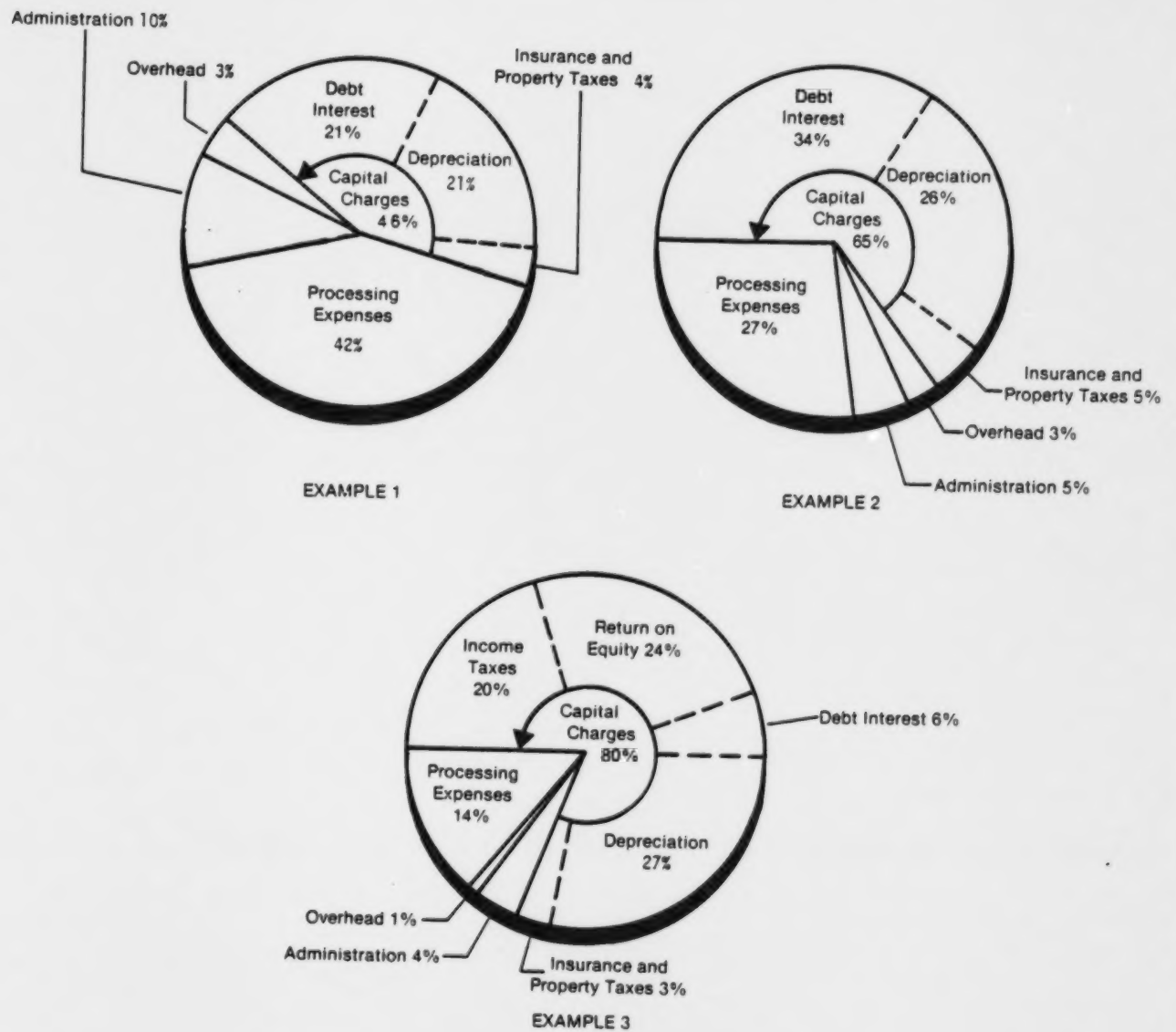


Figure 2-4. Total annual cost profile for three example systems.

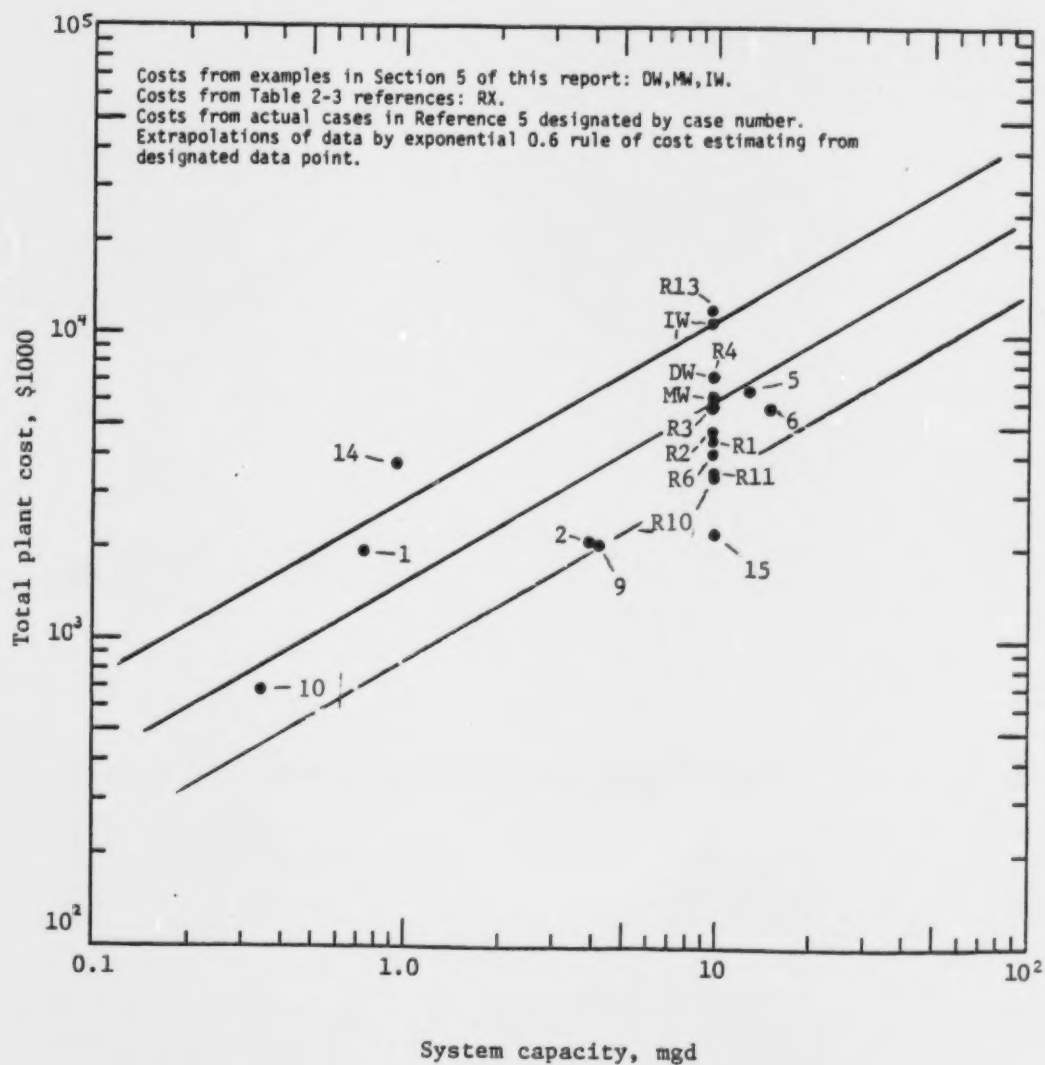


Figure 2-5. Granular activated carbon system capital cost from various sources.

investment, in most of the literature system costs are given as total plant cost or its equivalent^a. Therefore, the system costs from this report are plotted as total plant cost in this figure to make comparison with the literature on a common basis. Total capital investment requires that interest during construction, startup costs, land, and working capital be added to total plant cost. Points on the figure show the location of specific cases; the lines through the data are the result of applying the exponential rule of cost estimating to roughly estimate costs at a new system capacity if costs are known at another capacity^b. This was done to extend the results of the examples of Section 5 for comparison with literature reported costs over a wide range of system sizes. Individual estimates of many system sizes were beyond the scope of this study. Table 2-1 summarizes some of the data used in the figure.

A comparison for operation and maintenance (O & M) costs is made in Figure 2-6 where these costs are expressed as processing expenses. Again, literature costs are compared with costs developed in this report. Costs reported for actual systems were available only as totals, so there is no assurance that these costs are on a comparable basis to those used in this report. As with capital costs, all costs were updated to September, 1980 dollars.

The differences in these cost comparisons reflect variations in design, pricing, cost accounting and reporting, and estimating methodology. These cost comparison figures illustrate the importance of having a clearly specified design basis before attempting to make cost comparisons from different information sources. Even with the design basis specified, complete reconciliation of cost estimates or reported costs from different information sources can only be accomplished when pricing, accounting and reporting methods, and estimating methodology are also known for the different sources. A more detailed comparison between reported costs for an actual system and costs estimated using this report is presented in Appendix E.

2.5 COST ESTIMATING PROCEDURES

The fundamentals of cost estimating procedures upon which this document is based are presented elsewhere (12) and will not be discussed in detail here. However, certain key concepts do merit comment.

^aSee Subsection 2.5 of this report for definitions of total capital investment and total plant cost.

^bThis rule states that $C_B = C_A (Q_B/Q_A)^n$ where C is the cost at system capacity 'A', Q_A , and C_B is the cost at system capacity 'B', Q_B where n varies from .2 to 1.0. For GAC systems $n = 0.6$, approximately.

TABLE 2-1. CAPITAL INVESTMENT COST ESTIMATE COMPARISON AT 10 MGD REFLECTING DIFFERENCES IN DESIGN BASES, COST DATA, AND METHODS (Costs in thousands of dollars, September 1980)

Source Reference	Reference Publication Date on Cost Base Year	Total Plant Cost ^a (\$1000, Sept. 1980)	Cost Relative to Base Case (DW example case)	Percent Difference
DW base case example ^a	1981	7,010	1.00	0
MW base case example ^a	1981	6,000	0.86	-14
IW base case example ^a	1981	10,600	1.51	+51
Reference 3	1976	5,700	0.81	-19
Reference 4	1977	7,000	1.00	0
Reference 14 ^b	1979	7,000	1.00	0
Reference 13 ^c	1980	11,800	1.68	+68
Reference 1 ^d	1979	4,400	0.63	-32
Reference 11 ^e	1979	3,500	0.50	-50
Reference 10	1971	3,400	0.48	-52
Reference 15 ^f	1974	2,200	0.31	-69
Reference 6 ^f	1979	4,000	0.57	-43
Reference 2 ^k	1976	4,800	0.68	-32

^aDrinking water (DW), municipal wastewater (MW), and industrial wastewater (IW) example cases express total plant cost as defined by the format of this report. Costs based on Reference 3 and Reference 4 are believed to correspond to total plant cost. In the original references the term used was capital cost. Reference 14 expresses costs as total installed costs. It is not clear if this is equivalent to the total plant cost of this report or not. For purposes of this comparison it is assumed to be. Other references except Reference 7 provided sufficient information to adjust reported costs to conform to our definition of total plant cost. Costs were updated from earlier dates using the CE Plant Cost Index.

^bReference 14 expresses capital costs as total installed costs. It is not clear if this is equivalent to total plant cost. In this comparison it is assumed to be. Also, costs presented for a system at 3.9 mgd were used to derive costs for a system at 10 mgd. The derived cost is used in this comparison.

^cCosts given in Reference 13 were for a 283 mgd plant. For this comparison these costs were scaled down to 10 mgd using the exponential rule of cost estimating with an exponent of 0.6.

^dIn Reference 1 system costs were presented for 2 mgd, and 20 mgd. The exponential rule of cost estimating with an exponent of 0.6 was used to scale costs down from 20 mgd to 10 mgd for this comparison.

^eAmortized capital costs were presented in Reference 11. This was converted to total plant cost by using the 8% amortization rate and 20 year life given in the reference.

^fCosts in the reference were presented separately for the adsorption and regeneration systems. Regeneration costs were based on the same regeneration rate used in the DW example of Section 3, this report.

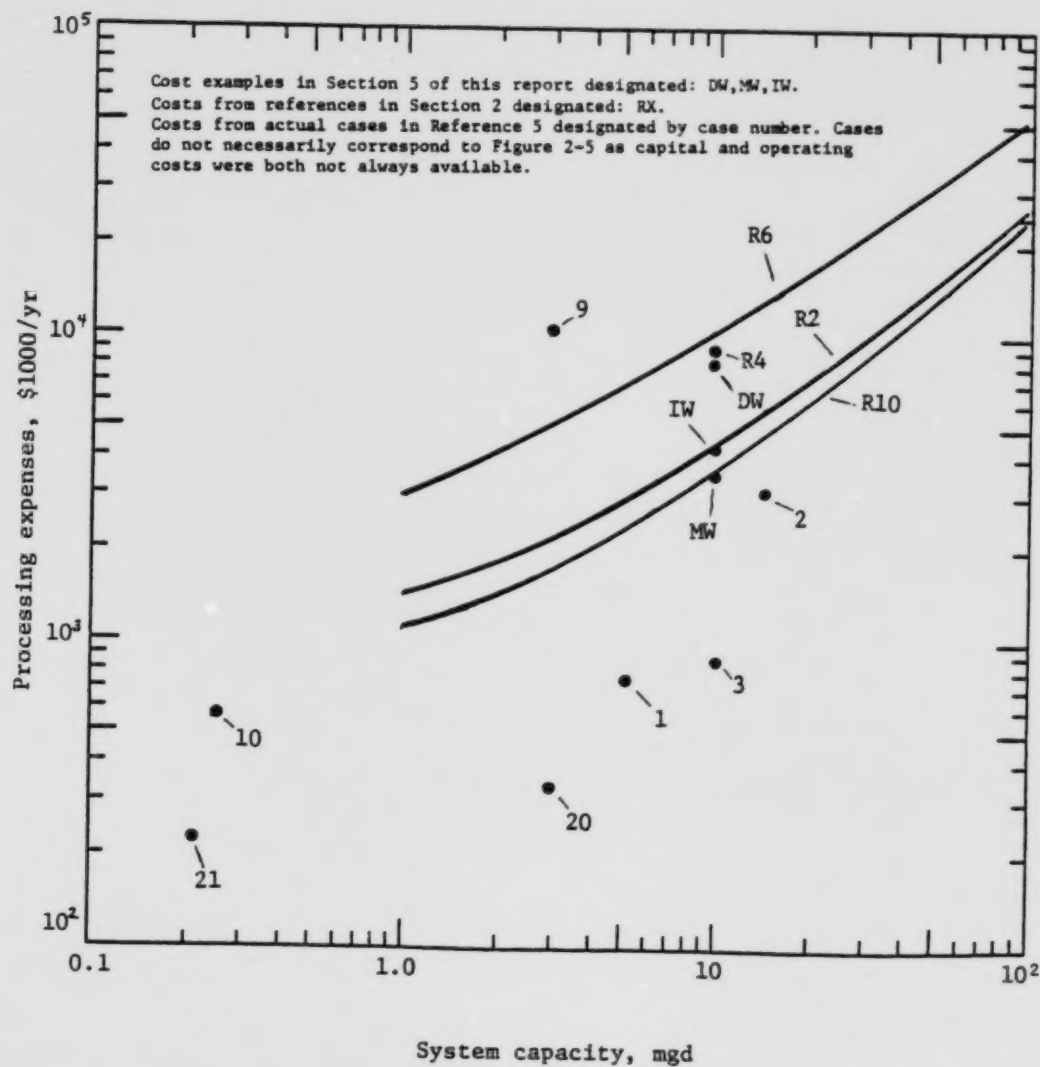


Figure 2-6. Granular activated carbon system processing expenses from various sources.

The format and terminology used for presenting costs are described in a report by Uhl (12). Introduction of a standardized, consistent format and terminology for control technology cost estimates is one of the goals of that document. The present report has tried to adhere to those procedures. Tables 2-2 and 2-3 define cost elements that comprise total capital investment and total annual cost for systems in this report.

2.5.1 Modular Costs

In Section 4 of this report, modular costs are provided to enable the user to develop a cost estimate for a specific GAC system. These costs include both direct capital costs (installed equipment costs) and processing expenses (operating and maintenance costs) for each individual module. The modular costs are added to obtain the corresponding level of system costs (direct capital costs and processing expenses). Then various adjustments are made to obtain total system costs in accordance with cost totals shown in Tables 2-2 and 2-3.

Direct Capital Costs

Direct capital costs include the purchased equipment costs and costs for installation labor and materials at the system site. Labor is for constructing foundations and support structures; setting the equipment; connecting piping, power, and other utilities as required; installing electrical components and instrumentation directly associated with the equipment; painting; and insulating. Engineering, field supervision, various field construction expenses and fees are not included in direct capital costs.

Processing Expenses

Processing expenses include expense items often referred to elsewhere as operating and maintenance (O&M) costs. Costs for the individual cost elements comprising processing expenses have been provided for each module for when appropriate. These cost elements are shown in Table 2-3 above processing expenses.

2.5.2 System Costs

The development of costs for systems is illustrated with three example cases. System costs can vary substantially depending on the outcome of numerous choices made for the system design variables. These variables depend on the individual water stream being treated, the treatment objectives required for that stream, and other site specific design choices. Examples shown are for systems that could be encountered for each application area. However, the examples do not necessarily reflect inherent differences between application areas. The examples, developed for the same flow rate in each case, illustrate how differences in system variables will be reflected in the system costs.

TABLE 2-2. FORMAT FOR TOTAL CAPITAL INVESTMENT

Item No. ^a	Item
1-10	Direct cost items
11	TOTAL DIRECT COST (Sum of items 1 - 10)
12-20	Indirect cost items (Engineering and supervision, construction and field expenses, other)
21	TOTAL BARE MODULE COST (Sum of items 11-20)
22	Contingency
23	Contractor's fee
27	Retrofit increment
24-26 , 28-30	Other
31	TOTAL PLANT COST (Sum of items 21-30)
32	Interest during construction
33	Startup
34	Other
35	TOTAL DEPRECIABLE INVESTMENT (Sum of items 31-34)
36	Land
37	Working capital
38 -40	Other
41	TOTAL CAPITAL INVESTMENT (Sum of items 35-40)

^aThese item numbers define a specific cost element as discussed in a report by Uhl (12). Where several item numbers are shown in this column, individual cost elements defined by those item numbers have been combined into the element shown in this table as a simplification for presenting cost data more concisely in this report.

TABLE 2-3. FORMAT FOR TOTAL ANNUAL COST

Item No. ^a	Item
53	Raw materials
56-58, 61	Labor
59, 60	Materials
62	Steam
63	Electricity
64	Compressed air
65	Water
66	Fuel
67	Waste disposal
68, 69	Other
70	PROCESSING EXPENSES (Sum of items 53-69)
71-73, 74	Overhead
76	Insurance and property taxes
77	Royalties
78	Depreciation
80	TOTAL OPERATING COSTS (Sum of items 70 and 74-78)
81	Administration
84	Average Interest on debt
87	AVERAGE TOTAL GENERAL EXPENSES (Sum of items 81-84)
82, 83, 88, 89	Other
90	TOTAL ANNUAL OPERATING EXPENSES (Sum of items 80 and 87-89)
- ^b	Average return on equity
- ^b	Average income taxes
- ^b	TOTAL ANNUAL COST (Sum of item 90, return on equity, and income taxes)

^aThese item numbers define a specific cost element as discussed in a report by Uhl (12). Where several item numbers are shown in this column, individual cost elements defined by those item numbers have been combined into the element shown in this table as a simplification for presenting cost data more concisely in this report.

^bNo item number was provided for these cost elements in Reference 12.

Total Capital Investment

Capital costs for systems are presented as total capital investment, defined in Table 2-2. Each item in the total is identified by an item number which ensures the unambiguous recognition of the item if the same procedure is used in other cost reports. Individual modular costs comprise cost items numbered 1-10 in Table 2-2. Other costs must be added to the total of these in order to obtain the total capital investment.

These other costs are obtained by multiplying a factor times a preceding cost value in the table. For example, indirect engineering costs are obtained by multiplying the total direct costs by the engineering cost factor. The total bare module cost is the sum of these costs, total direct costs and some other indirect cost items. One proceeds down the table item-by-item in a similar manner until total capital investment is obtained. The final result, of course, depends on the factors used. The cost factors used in developing the system costs are discussed in Section 5.

Total Annual Cost

Overall costs for activated carbon systems are presented as total annual cost. Total annual cost comprises both variable operating expenses and various relatively fixed capital charges. Total annual cost corresponds to the revenue requirement incurred by a project to cover its total cost, including the cost of capital invested in the project. Cost elements comprising total annual cost are shown in Table 2-3. Some of the non-capital related individual cost elements comprising total annual cost are obtained either by multiplying the annual operating requirements for the particular item by a unit price (for example, labor hours per year times labor rate of dollars per hour) or by applying a cost factor to a preceding cost item in the list. Individual prices and cost factors are discussed in Section 5. Capital charges include insurance and property taxes, administrative expenses, debt interest, depreciation, and for private sector projects, return on equity, and income taxes. Methods of computing these are discussed in Section 5.

2.6 SCOPE AND LIMITATIONS

The costs in this report are based on process modules which are representative of systems for water and wastewater treatment, although many design variations exist for these systems. Use of these costs will establish a baseline to which cost estimates and actual project costs using other designs, prices, or methods can be compared.

Costs in this report were developed from existing publications, unpublished cost data obtained from project files, and vendor contacts. Design concepts were developed from common engineering practice, the GAC literature, and study of the detailed engineering drawings of operating systems.

The overall accuracy of an estimate obtained by using this report is at the study estimate level with up to a $\pm 30\%$ potential variation.

Variations in costs of modules and systems can be expected both in estimation and during actual implementation of projects. Cost variations typically occur for three fundamental reasons;

- design definition (project scope and individual equipment specifications),
- prices, and
- project management.

Design definition refers both to the scope of a project and to the specifications associated with individual process modules and equipment. After certain major design criteria are established, many options remain available to a designer. Various combinations of these options can be used to achieve a satisfactory result. The scope of the project in terms of number of equipment items included and definition of battery limits and off-site boundaries, and the specifications for the various components in a module or system can have a significant impact on costs. Variations in costs should always first be examined in light of these considerations.

Price differences for the same equipment are due to individual vendor pricing practices and to many details that might not be apparent in the usual definitions of scope and specifications. There are temporal and geographic differences in labor and material costs for installation. Some of these factors can be partly compensated for by recognizing and using cost index or geographic locality factor adjustments. However, it must be recognized that prices are constantly changing. Although overall trends can be partially compensated for by using cost indices, the problem of accurately fixing prices relative to a given point in time will always exist. For budgeting a specific project, detailed equipment lists and current vendor and contractor quotations should be used rather than this or any other manual.

Finally, project management determines to some extent what the final cost of a real project will be. Cost control, scheduling, and effectiveness of response to unexpected events will determine the ultimate cost of a project.

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SECTION 3

PROCESS DESIGN CONSIDERATIONS

Design variability so significantly affects the costs of systems that an understanding of system design is required to understand the rationale for modular costs in Section 4 and system cost estimates and cost sensitivity analyses discussed in Section 5. The present section first describes adsorption and granular activated carbon systems in a general way. A discussion of types of systems and of design parameters follows. The section concludes with a discussion of applications and performance.

3.1 PROCESS DESCRIPTION AND DEFINITION OF PROCESS MODULES

Activated carbon adsorption is based on the ability of specially prepared carbon to adsorb and remove certain chemical species from a liquid solution that comes in contact with the carbon. In water and wastewater treatment, the carbon can be either powdered or granular, depending on particle size. Powdered activated carbon (PAC) consists of particles at and below U. S. Sieve Series No. 50. Granular activated carbon (GAC) consists of larger particles (1). Adsorption depends on the presence of micropores in the carbon particles. The adsorptive properties of the PAC and GAC are not fundamentally different since they depend on pore size and the internal surface area of the pores which are not dependent on overall particle size. In this report, only systems using granular activated carbon (GAC) are considered.

A number of grades of granular activated carbon are commercially available. Each has properties which makes it more suitable for certain applications than other grades. Besides adsorptive capacity and selectivity, these properties include the ability to withstand thermal regeneration without detriment to adsorption properties, and resistance to attrition losses during transport and handling. Table 3-1 lists some commercially available carbons (2). Detailed discussions of properties and comparisons of different carbons and adsorption mechanisms are available in published literature (3,4).

The practical application of granular activated carbon in water and wastewater treatment relies on the reuse of most of the carbon. During use, the carbon gradually becomes saturated with the species being adsorbed (adsorbate) so that it eventually loses its capacity to adsorb more material. Without a method to restore capacity for reuse, the carbon would be prohibitively expensive in all applications but those where carbon usage was small.

TABLE 3-1. PROPERTIES OF SEVERAL COMMERCIALLY AVAILABLE GRANULAR ACTIVATED CARBONS

Physical Properties	Type A	Type B	Type C	Type D
Surface area, m ² /g(BET)	600-650	950-1050	1000	1050
Apparent density, g/cm ³	0.43	0.48	0.48	0.48
Density, backwashed and drained, lb/ft ³	22	26	26	30
Real density, g/cm ³	—	2.1	2.1	2.1
Particle density, g/cm ³	2.0	1.3-1.4	1.4	0.92
Effective size, mm	1.4-1.5	0.8-0.9	0.85-1.05	0.89
Uniformity coefficient	0.8-0.9	1.9	1.8	1.44
Pore volume, cm ³ /g	1.7	0.85	0.85	0.60
Mean particle diameter, mm	1.6	1.5-1.7	1.5-1.7	1.2
Specifications				
Sieve size, U.S. std. series				
Larger than No. 8, max. percentage	8	8	8	—
Larger than No. 12, max. percentage	—	—	—	5
Smaller than No. 30, max. percentage	5	5	5	5
Smaller than No. 40, max. percentage	—	—	—	—
Iodine No.	650	900	950	1000
Abrasion No., minimum	—	70	70	85
Ash, percentage	—	8	7.5	0.5
Moisture as packed, Max. percentage	—	2	2	1

Source: Data from Reference 2.

The most common method for restoring carbon capacity is thermal regeneration or reactivation. (These terms are used interchangeably in the water treatment literature. In this report, the term regeneration is used.) Spent carbon is heated in a furnace to a high temperature. Adsorbed materials are driven off and burned. The process is controlled so that burning the carbon itself is avoided or minimized and carbon losses due to both oxidation and abrasive attrition are minimized. Regenerated carbon is then returned to the adsorbers for further service.

A conceptual diagram of a granular activated carbon system is shown in Figure 3-1. The system consists of a number of process modules comprising three major subsystems:

- carbon adsorption,
- regeneration, and
- carbon storage and transfer.

The heart of the system is the adsorber subsystem which consists of adsorbers containing the granular activated carbon. The influent water stream passes through the adsorbers where contact with the carbon removes stream contaminants. Backwash and surface wash equipment, as well as influent pumping can be considered as components of this subsystem.

Periodically, spent carbon is removed from the adsorbers and transferred to the regeneration subsystem for restoration of the adsorptive capacity of the carbon. Regenerated carbon is returned to the adsorbers, and some fresh makeup carbon is added to compensate for losses during transfer and regeneration.

The regeneration subsystem consists of the furnace, fuel system, air pollution control equipment for regenerator stack gases, and carbon furnace feed and discharge equipment.

The carbon storage and transfer subsystem consists of equipment for transfer of carbon between adsorbers and regeneration, as well as fresh carbon unloading, transfer and storage. Slurrying the carbon with water is the most common transfer method. Storage vessels are used for fresh carbon, spent carbon between adsorbers and regeneration equipment, and regenerated carbon between regeneration equipment and adsorbers.

Each of these major subsystems consists of various groupings of equipment items defined as process modules for convenience in developing cost data. Some process modules are considered which are auxiliary to the three subsystems discussed above. Details of process modules are discussed in Section 4 of this report.

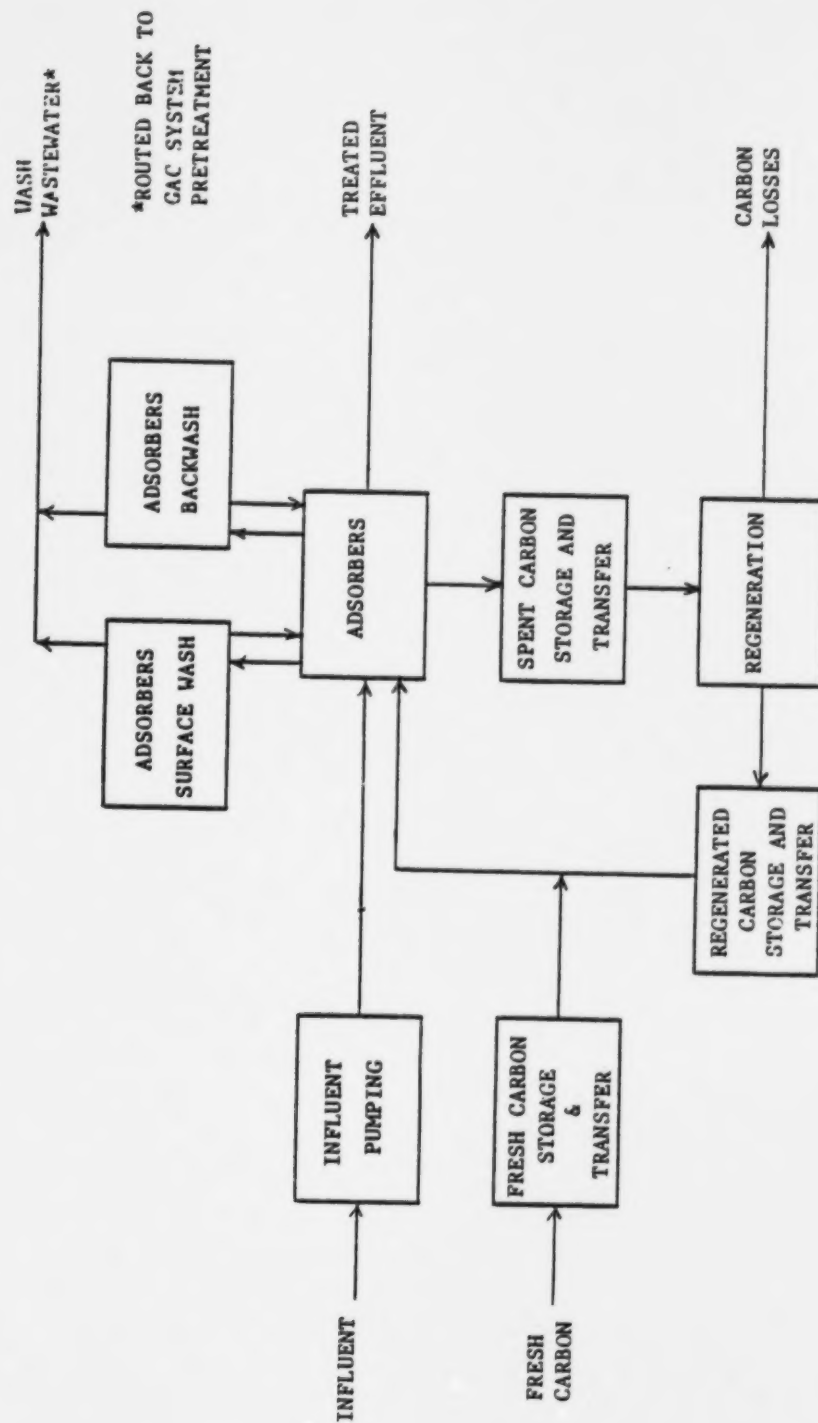


Figure 3-1. Granular activated carbon process modules.

3.2 TYPES OF ADSORBERS AND CONFIGURATIONS

Two fundamental types of granulated activated carbon adsorbers are fixed bed, and moving bed. In a fixed bed adsorber, the carbon contained in the adsorber remains stationary as the liquid flows through it. Fixed bed adsorbers can operate with liquid flow downward (downflow) or upward (upflow). Moving bed adsorbers, on the other hand, operate in upflow. An expanded moving bed adsorber operates at a flow rate high enough to cause the carbon bed to expand slightly. A pulsed-bed adsorber, the second type of moving bed, is periodically "pulsed" to discharge a portion of the exhausted carbon from the bottom of the bed while a slug of fresh carbon is added at the top. The liquid and carbon move in true countercurrent flow to each other.

Single or multiple adsorbers can be used depending on the requirements. Multiple adsorbers can be arranged as individual vessels in a series or in parallel, or as combinations of series units in parallel. These methods each have certain functional advantages depending on the requirements of each individual application. Figure 3-2 illustrates the fundamental adsorber types and configurations. Table 3-2 lists the basic differences in selection criteria for the various adsorber configurations (5,6,7).

3.2.1 Fixed Beds in Series

In this configuration, the flow is downward through the carbon bed for each unit in the series. When carbon is removed for regeneration, the first adsorber in the series is shut down with the next adsorber in line becoming the lead unit. This system can be built with an extra column on standby to become the last column when the lead column is taken out of service. Capital cost considerations usually limit the number of columns in series to four or fewer (8). This arrangement causes the total carbon charge of the system to approximate countercurrent flow to the water stream. Approaching countercurrent flow provides highly efficient usage of the carbon by maximizing the exhaustion of the carbon in the lead column before it is removed for regeneration. Backwashing can be used on the lead column to remove limited amounts of suspended solids that accumulate in the carbon bed.

3.2.2 Fixed Beds in Parallel

With the parallel arrangement, each carbon bed receives the same quantity and quality of influent stream. Startup of the individual units is staggered so that exhaustion of the carbon occurs sequentially. This allows removal of the entire bed of carbon from each adsorber, one at a time, for regeneration. For systems operating at full design capacity, a spare adsorber can be provided to come on stream when another adsorber is taken out of service.

In this system, the level of carbon exhaustion when a bed is discharged is not as high as that of fixed beds in series because no bed is run completely to breakthrough^a. The carbon utilization in a given column can,

^aSee Subsections 3.3.2, 3.3.3, and 3.3.4 for a definition and discussion of breakthrough.

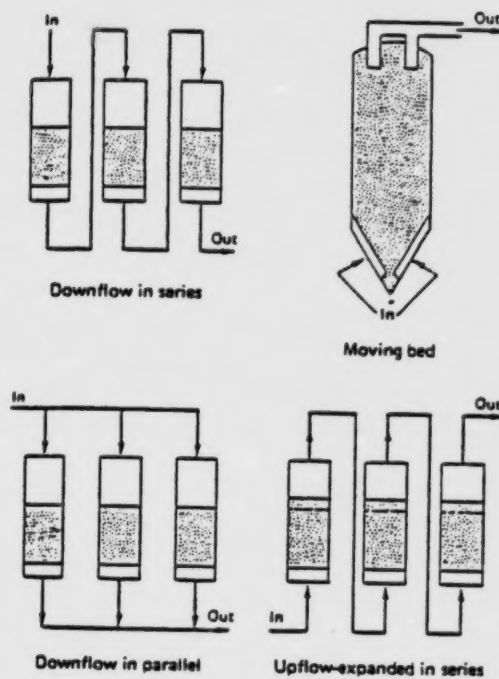


Figure 3-2. Common configurations for granular activated carbon systems.

TABLE 3-2. GUIDE TO SELECTION OF GAC SYSTEM CONFIGURATION (5,6,7)

Absorption System Configuration	Applicable when:
Single Column	Low carbon exhaustion rate (usage rate) occurs. Unusual temperature or pressure conditions must be used in the column.
Fixed Beds in Series	High carbon exhaustion rate occurs. Gradually sloping breakthrough curve is demonstrated. High effluent quality must be assured at all times.
Fixed Beds in Parallel	High system pressure drop is minimized. Large total flow rate is required.
Moving Beds, Upflow ^b	High carbon exhaustion rate occurs. High effluent quality is required. Some carbon fines can be tolerated in the effluent or carbon adsorption is followed by filtration.
Expanded Beds, Upflow	High suspended solids are present in the influent, and some suspended solids can be tolerated in the effluent.
Combined Series and Parallel	Combined features of respective configurations are required.

^aSee Section 3.3.2 of this report for definition and discussion of breakthrough.

^bThese systems can use either a pulsed bed or a continuously moving bed. Water flows upward and a carbon slurry is removed from the bottom of the bed while fresh carbon is added to the top. This results in a countercurrent operation with high carbon utilization and minimum adsorber volume. The total amount of carbon removed from the bed per pulse amounts to about 5-10% of the total bed volume (7).

however, be increased by blending effluent from all the columns. One or more columns can be run slightly beyond the breakthrough point, while others are not allowed to reach such a high level of carbon exhaustion which would be the obvious way to run parallel adsorbers while still ensuring meeting the treatment objective. By blending the effluent a specific treatment objective could still be met while maximizing carbon utilization. This technique, combined with staggered operation, allows some columns to operate at higher effluent concentrations than the final desired concentration by averaging effluent streams with high and low concentrations.

This configuration is most appropriate for larger plants where total flow would require prohibitively large single adsorbers, at plants with highly variable flows where high turndown flexibility is needed, and where adsorption characteristics and treatment requirements permit blending to meet effluent criteria.

3.2.3 Expanded Beds

Expanded beds permit removal of suspended solids by periodic bed expansion and diversion of the adsorber effluent with disposition analogous to the backwash stream of a downflow adsorber. In general, expanded beds can tolerate relatively high suspended solids while using finer carbon particle sizes without excessive head loss. Expanded beds cannot be used where downstream contamination by suspended solids passing through the bed would be a problem.

3.2.4 Pulsed Beds

A design and operational mode that always operates in upflow is the pulsed bed. In this system, the water and carbon flow is countercurrent. Pulsed-bed adsorbers permit intermittent or continuous removal of spent carbon from the bottom of the bed while fresh carbon is added at the top without system shutdown. The chief advantage of this system is better carbon utilization because only thoroughly exhausted carbon will be regenerated, in contrast with fixed beds where a single bed cannot be completely exhausted lest some contaminant break through into the effluent causing the effluent criterion to be exceeded. (This possibility is reduced in fixed-bed operation by placing two beds in series. The second bed acts as a guard.)

Another characteristic of the pulsed bed system is that a steady-state constant effluent concentration (assuming a constant influent concentration) is achieved. In fixed beds, the effluent concentration gradually increases with time. This is discussed further in Section 3.3.2.

3.2.5 Downflow vs. Upflow Operations

Downflow is appropriate when the carbon bed is to be used as a suspended solids filter as well as an adsorber. The suspended solids are periodically

removed by backwashing in a manner identical to that used with granular media filters. When the carbon adsorber is preceded by granular media filtration, downflow can sometimes be used without backwashing or with reduced backwashing.

Upflow adsorbers are appropriate for influents with either high or low suspended solids concentrations. For high suspended solids concentrations upflow might be preferred because solids accumulation and corresponding head losses would be excessive in downflow adsorbers. In such an application some downstream solids must be tolerated, or the adsorbers must be followed by filtration. For low suspended solids concentrations, upflow can be used because the carbon bed is not needed as a solids filter.

3.2.6 Gravity Flow vs. Pressure Flow

Gravity flow is likely to be used only in downflow beds unless construction on sloping land permits sufficient hydraulic gradient for a gravity-fed upflow.

Pressure flow can be used for either downflow or upflow beds. A reason for using pressure flow is to achieve higher hydraulic loadings (gallons per minute/square foot of adsorber cross-sectional area) than would be possible with gravity flow. This higher loading reduces the adsorber cross-sectional area required. Pressure flow also permits operation at higher suspended solids concentrations with no backwashing or with less frequent backwashing than would be possible with gravity flow. This is because there is sufficient head to overcome bed pressure drop (head loss).

3.3 DESIGN PARAMETERS FOR ADSORBERS

The design of a granular activated carbon adsorption system depends on influent characteristics and treatment objectives (the effluent characteristics). The treatment objective establishes the performance needs for the system; the characteristics of the influent stream affects the choice of system configuration and equipment size necessary to achieve the required performance. The overall economics of the system are heavily dependent on trade-offs between the size of the adsorbers and the size and operating requirements of the carbon regeneration subsystem. The operability and economics of the overall system also depend on proper design of carbon storage vessels and equipment required for carbon transfer between the adsorption and regeneration portions of the total system.

Each of the three subsystems defined earlier has associated with it several key design parameters as shown in Table 3-3. Values shown in the table are typical and may vary with specific applications. These parameters are determined by the influent characteristics and effluent treatment objectives for a given system. In the following paragraphs, these parameters are discussed for each subsystem and their influence on design of process modules is explained.

TABLE 3-3. TYPICAL DESIGN PARAMETER RANGES FOR GAC SYSTEMS^a

Subsystem	Parameter	Typical Values
Adsorbers	Carbon Type	Varies with application.
	Contact Time	10 - 120 min.
	Breakthrough Characteristic ^b	Varies with influent properties and carbon type.
	Hydraulic Loading	2 - 10 gpm/ft ²
	Backwash Frequency and Rate	15 - 20 gpm/ft ² , for periods of 10-20 minutes several times a day
Regeneration	Carbon Throughput Rate	Up to 50,000 lb/hr per unit
	Operating Temperature	1200 - 1900°F
	Residence Time	10 min - 4 hrs, depending on regeneration method and the nature of the materials adsorbed on the carbon
Carbon Storage and Transfer	Slurry Flow Rate	Varies with discharge interval selected by designer
	Regeneration Frequency	Intermittent and variable; usually several weeks to months
	Carbon Losses	5 - 20% of regeneration quantity

^aCompiled from various literature sources.

^bThis is the relationship between effluent concentration, contact time, and total volume of water processed or time elapsed. It can be experimentally determined for any adsorber or estimated by mathematical modeling. Breakthrough is discussed in Sections 3.3.2 through 3.3.4 of this report.

3.3.1 Carbon Selection

The first consideration in the design of any activated carbon system is the selection of the carbon itself. This selection depends on the ability of a given carbon to remove the contaminants of concern and to meet other system requirements related to pressure drop (head loss), carbon transport, and regeneration.

The fundamentals of activated carbon adsorption theory are discussed in published literature (4,9) and will not be repeated here. A number of granular activated carbons are commercially available, and the type most suited for a given application is usually determined by laboratory and pilot testing. Although mathematical models (10,11) have also been developed to predict adsorption behavior in carbon systems, the complexity of most systems still requires experimental design data. However, models can be useful for preliminary design and cost analyses where an estimate of performance may be required.

Granular activated carbons in common use are available in two particle sizes: 8x30 and 12x40 mesh. These size designations are based on 95% of the carbon passing through the mesh size for each case.

3.3.2 Contact Time and Breakthrough

Two important variables in carbon selection tests are contact time and the breakthrough characteristic. These variables, along with flow quantity, determine carbon bed and adsorber volume. The carbon exhaustion or usage rate, which is related to the breakthrough characteristic, will determine the size of the regeneration system. Size of the adsorbers and regeneration system and scheduling of carbon transfer between these two systems determines carbon transfer and storage requirements.

Empty bed contact time is the superficial flow rate of the fluid stream through the adsorber divided by carbon bed volume. Adsorber volume depends on bed volume and how much freeboard or excess vessel capacity over bed volume is provided. This may range up to about 50 percent for fixed bed and expanded bed systems. If bed expansion is not required, even with backwashing to remove collected solids, a freeboard of 20-30 percent may be adequate. Virtually no freeboard is required for upflow pulsed beds.

Contact time can be varied by changing bed depth at constant flow, and changing flow at constant bed depth. The effect on performance is to alter the time to breakthrough for a column. Breakthrough is defined as the point where the solute concentration in the adsorber effluent exceeds the treatment objective. Shorter relative contact times result in earlier breakthrough; longer relative contact times delay breakthrough. There is clearly an economic tradeoff between breakthrough frequency and adsorber volume.

In addition to postponement of breakthrough for simple systems up to a certain point, carbon utilization improves as contact time increases. The

percentage of total carbon in the bed that is exhausted at breakthrough is greater in a deeper bed than in a shallower bed. Beyond a certain point, however, additional adsorber volume merely acts as storage capacity for spent carbon. This is similar to the way in which excessive bed depth provides storage volume for unexhausted carbon prior to the arrival of the moving boundary between exhausted and unexhausted carbon within the bed. There is, therefore, an optimum bed depth from the perspective of adsorber cost alone. The actual choice of bed depth and corresponding adsorber volume, however, also depends on regeneration frequency. A tradeoff exists between increased adsorber volume with reduced regeneration rate and reduced adsorber volume with increased regeneration rate. The optimum bed depth and the tradeoffs will depend on individual system influent and carbon bed characteristics.

3.3.3 Breakthrough Characteristics

Whereas breakthrough is defined to occur when the effluent concentration exceeds some pre-set value, the breakthrough characteristic is a continuous function of effluent concentration versus total volume of water treated, or versus time. Breakthrough is described mathematically by solution of the differential equations describing adsorption. Figure 3-3 illustrates a typical breakthrough characteristic and relates it to the relative amount of the carbon bed exhausted, still active (adsorption zone), and as yet relatively free of adsorbed material. At startup, effluent emerging from the column has a very low concentration of solute. Most of the solute has been adsorbed by the carbon near the beginning of the bed. As more liquid flows through the column, the adsorption capacity of the carbon is exhausted, less solute is adsorbed, and a gradual increase in effluent solute concentration occurs. Finally, as the bed nears exhaustion, the effluent solute concentration increases rapidly as it approaches the influent solute concentration.

Breakthrough depends on the characteristics of both the influent stream and the carbon bed. Different solutes with different carbons will yield different slopes for breakthrough curves at a given flow rate and bed depth (i.e., a given contact time). Also, the time interval from startup to the breakpoint shown in Figure 3-3 will depend on the specific solute and carbon. The two physical-chemical variables for a given system which determine these breakthrough characteristics are the equilibrium constant and the rate constant for adsorption.

Changing the contact time by changing bed depth or flow rate through the carbon bed might alter the shape of the curves as well as displacing them along the abscissa. This is illustrated in Figure 3-4. Also shown is the corresponding carbon exhaustion rate curve. Carbon exhaustion rate determines the regeneration requirements of the system.

Breakthrough curves are important to design because they define the relationship between the physical-chemical parameters of the solvent-solute-carbon system, flow rate, bed size, carbon exhaustion rate, the selection of the number of columns in a series multi-adsorber system, and the treatment objective.

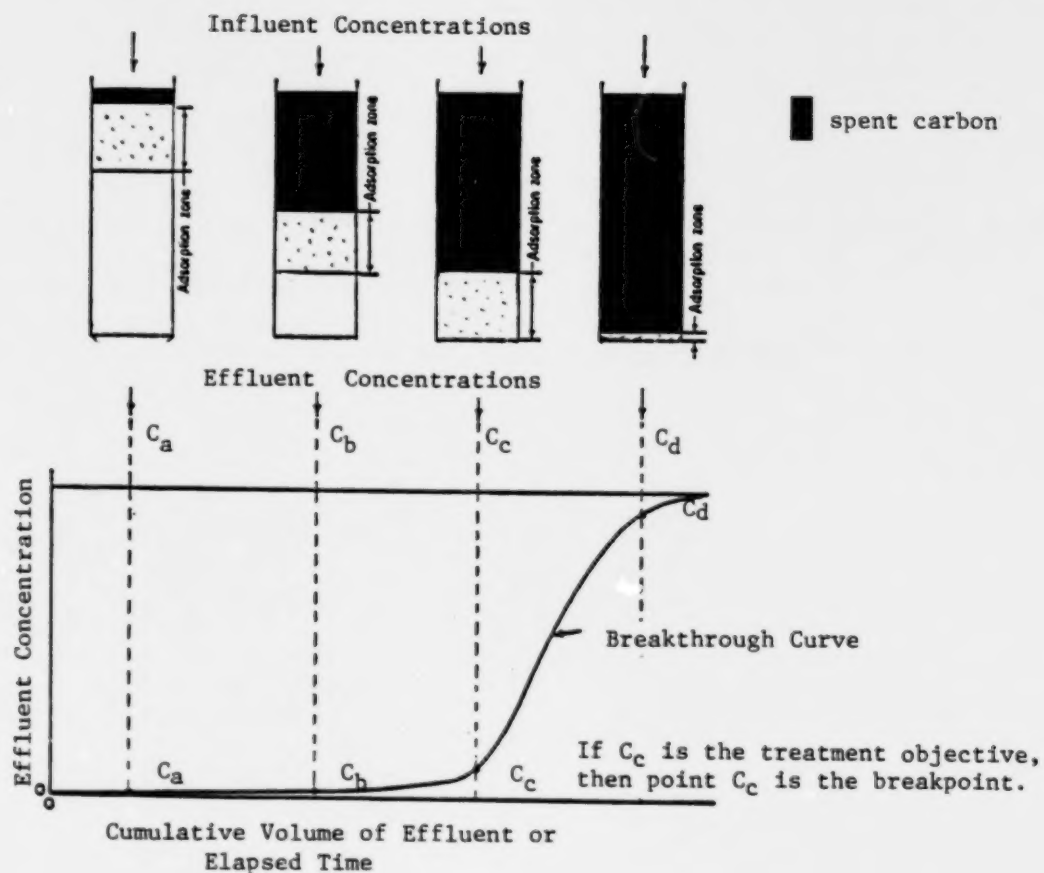
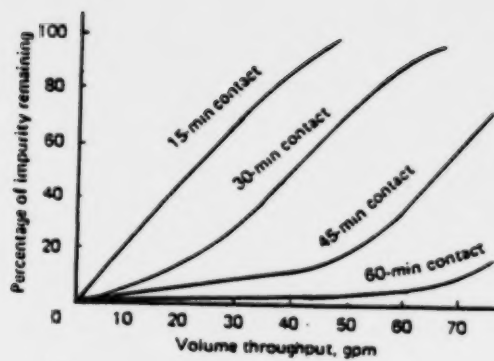
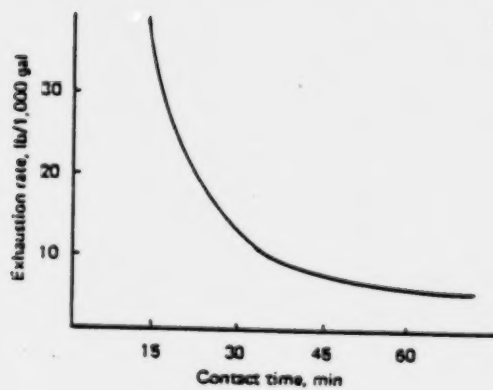


Figure 3-3. Passage of adsorption wave through a fixed bed and corresponding breakthrough curve.



(a)



(b)

Figure 3-4. Typical carbon adsorption breakthrough curves showing effect of contact time (a); and corresponding exhaustion rate curve (b).

Adapted from Reference 13.

3.3.4 Breakthrough and System Design

There is a relationship between the breakthrough characteristic, treatment objective, and number of adsorbers. Consider first a single adsorber. Refer to Figure 3-5. Three treatment objectives are illustrated and labeled A, B, and C along with their corresponding effluent concentrations and times on stream. Consider A as a baseline treatment objective. When a lower effluent concentration than A is required, the time on stream for the carbon bed is reduced from t_A to t_B . For a given contact time, the design implication is that the carbon exhaustion rate is lower, carbon dosage is higher, and regeneration must be more frequent. In moving from t_A to t_B , the exact opposite is true.

For a fixed treatment objective, analysis of several breakthrough curves for the influent under study provides the information needed to size the adsorber and regeneration systems. The contact time selected for design will be the one which yields a reasonable adsorber volume and regeneration frequency. The reasonableness depends on the cost tradeoff between having a large carbon bed and adsorber volume with less frequent regeneration, and a smaller adsorber volume and more frequent regeneration.

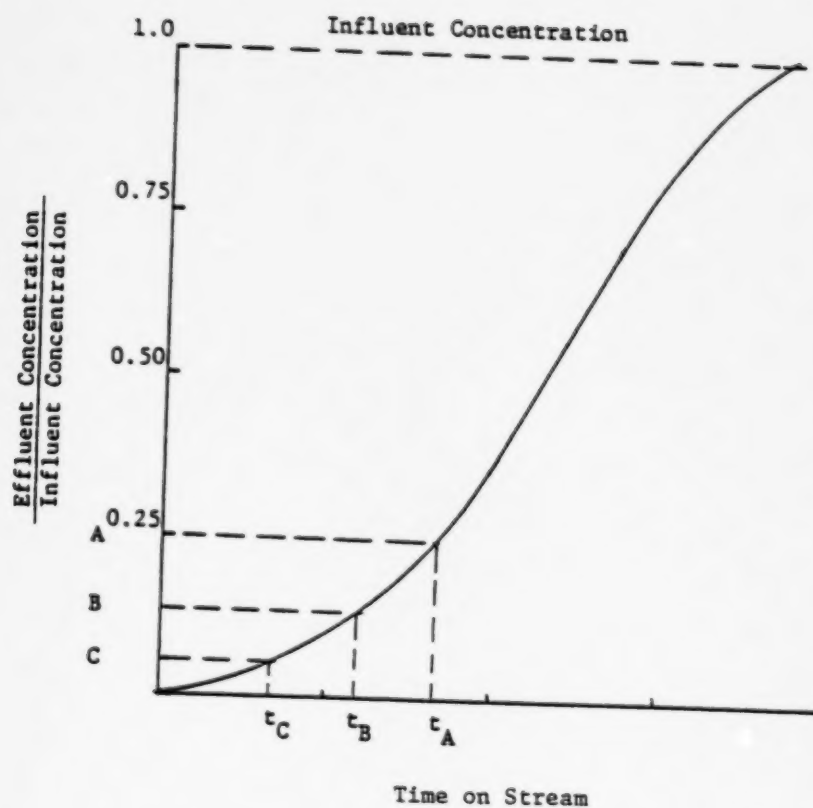
In addition to frequency of regeneration, the breakthrough curve also provides information for estimating the minimum regeneration rate required. If the changeover time for emptying spent carbon and recharging regenerated carbon in an adsorber is negligible compared to total on-stream time, then the minimum time interval in which the carbon is regenerated must equal the length of on-stream time before breakthrough. This is to ensure that regenerated carbon will be ready to fill the adsorber just as the carbon in use is exhausted. In practice, of course, surge storage capacity is provided so that the actual regeneration rate can differ from the value obtained using this minimum regeneration time interval.

In practice, multiple beds in series can be used. When one bed is exhausted and ready for regeneration, the next bed still has some capacity left. This ensures that the treatment objective will not be exceeded at any time. Carbon transfer to the regeneration system is more frequent, but if the total volume of the two series beds is equivalent to the volume for a single bed to accomplish the same treatment objective, the regeneration feed rate of carbon is unchanged.

Although the breakthrough characteristic can be used to size pulsed beds, it is not observed in them. Pulsed beds maintain a near steady-state effluent concentration when operating properly. Actually, of course, effluent concentration fluctuates with fluctuations in influent concentration.

3.3.5 Hydraulic Loading

Hydraulic loading is the quantity of liquid flowing through the bed per unit of cross-sectional area. It is expressed as gallons per minute per square foot (gpm/ft²). Once the required contact time is selected for a given



At a constant bed volume, as the treatment objective moves from A to C requiring a lower effluent concentration, time on stream (i.e., time to regeneration) decreases. Conversely, at a constant on-stream time required before breakthrough occurs, the bed volume increases as the required effluent concentration is reduced.

Figure 3-5. Breakthrough curve and alternative treatment objectives for fixed bed operation.

performance objective, the cross-sectional area of the adsorber is selected to ensure that hydraulic loadings are in a reasonable operating range of 2 to 10 gpm/ft².

Two considerations determine the permissible hydraulic loading in GAC:

- superficial bed velocity, and
- head loss through the bed.

In the normal operating range for hydraulic loading, superficial bed velocity does not appear to critically affect adsorption rates (15). However, there is evidence that for some materials, changes in superficial velocity do affect performance (15). This is consistent with the well established principles of mass transfer from moving fluid streams. In the context of this report, further discussion of this area is not necessary. Head loss through the carbon bed is a more dominant concern in the selection of hydraulic loading.

Estimation of head loss is discussed in more detail elsewhere (15,16). In addition to flow rate and influent solids concentration, head loss also depends on carbon particle size and type. Figure 3-6 shows clean bed head loss curves for several commercially available carbons. The permissible head loss also depends on whether gravity or pressure is used in downflow.

Because of head loss, the acceptable loading for any liquid stream depends on the quantity and characteristics of suspended solids present and their tendency to plug the bed. Downflow beds are more subject to plugging than upflow beds. In upflow, there is a tendency for particles to settle away from the upstream end of the bed (since in upflow, upstream is the bottom of the bed), thus preventing surface blinding and penetration of solids into the bed. Also, upflow beds are easily expanded so that solids can wash through. In downflow, the accumulation of solids at the surface and within the bed is favored, and bed expansion can be achieved only in a backwash cycle. In some applications the carbon is used deliberately as a filter as well as an adsorber; in which case, the downflow arrangement is preferred. Commonly, carbon adsorption is preceded by granular media filtration to reduce suspended solids concentration and the resulting head losses.

Typical ranges for hydraulic loading are 2-5 gpm/ft² for downflow beds and 5-10 gpm/ft² for upflow beds. It has been recommended that for gravity downflow, hydraulic loading should be limited to less than 4 gpm/ft², but for pressure downflow, this maximum value can be increased. For upflow expanded beds, 6 gpm/ft² for 8x30 mesh carbon is acceptable. Other recommendations based on configurations are given in Table 3-4.

3.3.6 Backwashing

Backwashing is the reverse flow of clear liquid through a carbon bed to dislodge and remove accumulated suspended solids. Frequency of backwashing

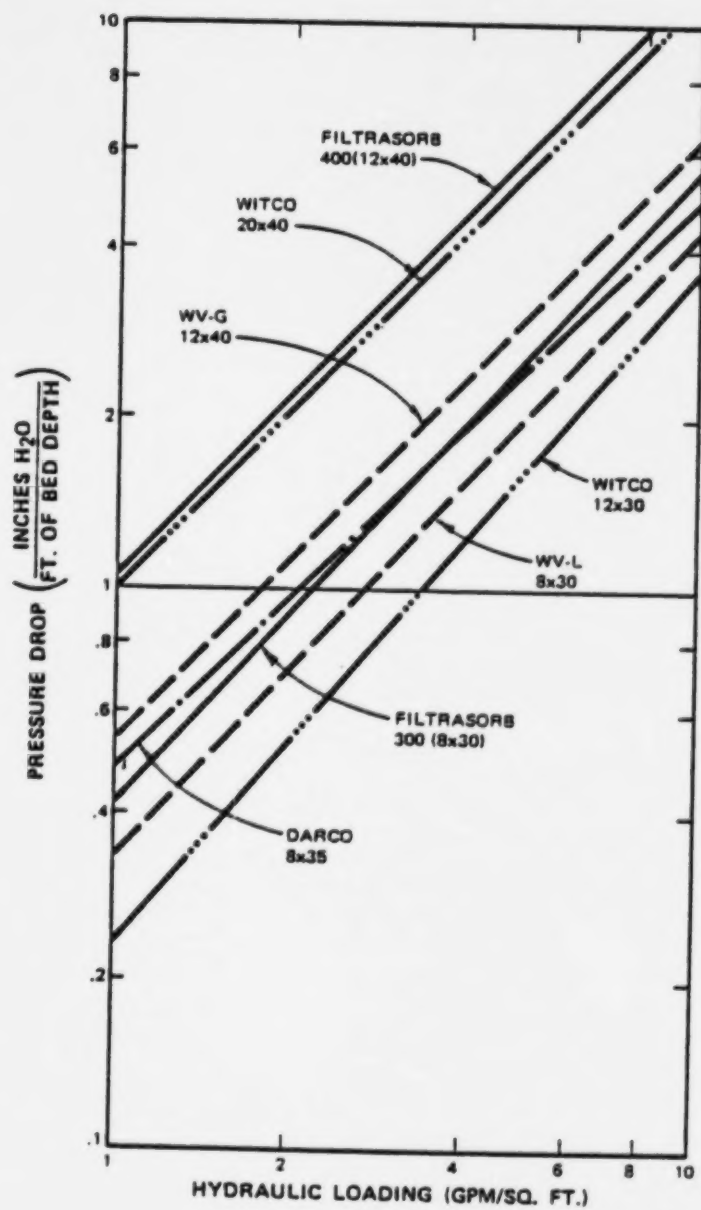


Figure 3-6. Carbon bed pressure drop vs. hydraulic loading.

Source: Reference 16.

TABLE 3-4. TYPICAL HYDRAULIC LOADINGS FOR DIFFERENT ADSORBER SYSTEM CONFIGURATIONS

Configuration	Hydraulic Loading (gpm/ft ²)
Parallel and single column fixed bed	1 - 4
Series beds	3 - 7
Pulsed-bed systems	5 - 9

Source: Data obtained from Reference 15.

depends on the rate of head loss, and the rate of increase in effluent suspended solids concentration. The quantity of backwash water depends on the amount and characteristics of the accumulated solids. Backwash frequency and quantity depends, therefore, on the interaction of hydraulic loading and other system variables previously discussed.

The frequency of backwash must be selected to ensure adequate solids removal and prevention of compaction of accumulated solids. A guide to selecting backwash frequency is that no more than 5% of the treated clean water should be required for backwashing (16).

Supplements to backwashing are air scouring and surface washing. Air scouring is introducing compressed air at the bottom of the bed during backwashing to increase turbulence and loosen deposited solids. Its benefits must be weighed against the potential for increased carbon losses due to abrasive attrition. Surface washing is the application of water jets to the upstream surface of the bed to loosen compacted solids. Systems with backwash do not necessarily use these supplementary operations.

3.3.7 Adsorber Characteristics

Adsorbers are cylindrical vessels or rectangular boxes of steel or concrete. The type of vessel used depends on system size, configuration, influent characteristics, and individual designer preference.

Three fundamental adsorber types are:

- open-top steel, gravity flow,
- closed steel, pressure flow, and
- open-top concrete, gravity flow.

Each has preferred applications. For example, industrial wastewater applications in the range of 1-10 mgd would usually employ pressure steel vessels. Large municipal systems greater than 10 mgd might use open top concrete adsorbers. Basic characteristics of adsorbers are summarized in Table 3-5. Other features that differentiate individual adsorbers are the details of internals such as liquid distributors and collectors and carbon bed support methods (16,17). Schematics of both steel and concrete adsorbers are shown in Section 4.

The sizing of an adsorber is based on flow rate, hydraulic loading, and contact time. These variables yield adsorber volume, height, cross-sectional area, and number of individual parallel adsorber vessels. Once these quantities are known, the adsorber layout plan can be developed.

TABLE 3-5. BASIC CHARACTERISTICS OF ADSORBERS

Adsorber Type	Material	Volume Range	Diameter	Remarks
steel, gravity flow	lined carbon steel	6,000 - 200,000 ft ³	20 - 30 ft.	Field fabricated by welding or bolting pre-formed steel plate. Mounted on concrete slab foundation.
steel, pressure flow	lined carbon steel; stainless steel	2,000-50,000 ft ³	Up to 12 ft.	Shop fabricated; over-the-road transportation constraints limit size.
concrete, gravity flow	standard reinforced concrete	1,000-200,000 ft ³	usually rectangular	Field constructed. Designs vary. A 2:1 length to width ratio is common.

Source: Data obtained from Reference 18.

3.3.8 Adsorber Layout Plans

A variety of adsorber layout plans are possible, but standard good engineering practice suggests that certain fundamental approaches be used in all installations. The layout plan depends on the type of adsorber and size of the plant. A fundamental distinction is between circular and rectangular vessels.

Circular Adsorbers

Circular adsorbers include both pressure and gravity flow steel vessels. In at least one instance, circular concrete adsorbers also have been used in a granular activated carbon plant (19). Use of adsorbers in parallel or series affects the equipment layout.

A first consideration in developing a layout plan is whether or not to use multiple adsorbers in series. Next is to determine how many parallel adsorbers or parallel sets of series adsorbers are required for a given design capacity. For the fixed bed case, at least two adsorbers in series is a likely configuration. (The reason for using the series arrangement is to maximize carbon utilization in the lead adsorber while having the follower adsorber as a guard to prevent exceeding the specified treatment objective.) These series pairs would constitute an adsorber module which can be repeated as required to achieve total plant design capacity with parallel modules.

The single adsorber is an unusual situation except for a pulsed-bed unit. Since only a portion of exhausted carbon is discharged while the pulsed-bed unit continues to operate, a second bed in series to ensure meeting the effluent requirement while maximizing carbon utilization is not required. Pulsed-bed units can also operate in parallel for large flows.

Selection of the Size and Number of Parallel Circular Adsorbers

Selection of the number of adsorbers for any given design capacity depends on vessel size, and permissible hydraulic loading.

Commercially available steel adsorbers usually have standard diameters. Shop-fabricated steel vessels are limited to 12 ft. in diameter and 60 ft. in length by over-the-road transportation constraints. Standard diameters, according to the ASME code for unfired pressure vessels, are given in Table 3-6 for shop-fabricated and field-fabricated steel vessels (20).

If the flow is divided equally between adsorbers in a group so that the hydraulic loading is the same for each, then the cross-sectional area required is simply the flow rate divided by the hydraulic loading, in consistent units. The number of adsorbers is this total cross-sectional area divided by the cross-sectional area of one adsorber. If hydraulic loading is critical, the result can be rounded up to the next whole number of vessels to allow for fluctuations in hydraulic loading.

TABLE 3-6. STANDARD DIAMETERS FOR CIRCULAR STEEL VESSELS

Shop Fabricated	Field Fabricated
7' - 11''	15' - 6''
9' - 6''	21' - 6''
10' - 0''	29' - 9''
11' - 0''	38' - 8'' not likely for GAC
12' - 0''	55' - 0'' adsorbers

Source: Data obtained from Reference 20.

Rectangular Adsorbers

Rectangular concrete adsorbers are commonly used for municipal drinking water or wastewater facilities that use GAC treatment. Multiple vessels are generally built into a large concrete structure with individual vessels sharing a common wall. Sometimes the overall structure is part of a building foundation. Design details for structural support and influent, effluent, carbon slurry, and backwash inlets and outlets vary from plant to plant.

An analysis was made of drawings of actual facilities to develop some simplified standards for rectangular concrete adsorber costs presented in Section 4. Two major design features subject to variations are the length-to-width ratio of a vessel and the design of influent and effluent channels.

A typical flow cross-section for rectangular concrete adsorbers is a 2:1 length-to-width ratio. This is consistent with designs observed in the field (21) and in drawings of actual facilities.

The structural cross-section depends to some extent on the influent and effluent channel design. Structurally, concrete adsorbers can be relatively simple or complex. The level of complexity influences the cost of a system. This is recognized in the modular costs presented in Section 4.

3.4 REGENERATION SYSTEMS

Three potential regeneration techniques are chemical, steam, and thermal. Both chemical and steam regeneration are used primarily in industrial systems designed to recover the adsorbate. They have not been used in water and wastewater treatment systems since they do not adequately regenerate the carbon for uses requiring removal of organics present in very low concentrations. Thermal regeneration is the regeneration method commonly used in water and wastewater treatment systems; therefore, it is the only method which will be discussed in detail.

Thermal regeneration is made up of four stages: drying, desorption, pyrolysis, and gasification. The granular carbon is usually transported to the regeneration equipment in a water slurry. The carbon is dewatered to about 50 percent water by weight in a dewatering feed screw to the regeneration furnace. Drying occurs in the entry zone as the carbon is heated from ambient temperature to 212°F. Thermal desorption followed by pyrolysis of the organic adsorbates occurs as the temperature increases beyond 212°F. Gasification occurs between 1200°F and 1900°F.

In the desorption step, volatile materials that are not strongly adsorbed to the carbon are driven off as they are heated; then heavy organics are pyrolyzed forming residual char on the carbon. Finally, during the gasification stage, the desorbed vapors and gaseous products of pyrolysis leave the pores of the particles. During this stage the char is burned. Regenerated carbon generally does not have the same adsorption characteristics as new carbon. This is partly due to enlargement of the pore sizes during pyrolysis and the adsorption of some inorganic compounds from the water which are not removed in regeneration.

After the regeneration is completed, the hot carbon is cooled in a water-filled quench tank.

Four different thermal regeneration systems are:

- rotary kilns,
- multiple hearth furnaces,
- fluid-beds furnaces, and
- infrared furnaces.

The first two techniques are the traditional methods of granular activated carbon regeneration. Fluidized beds and infrared ovens have been applied more recently. Because they are more energy intensive, rotary kilns do not appear to be competitive with the other procedures at the present time and will not be discussed further.

3.4.1 Multiple Hearth Furnaces

Multiple hearth furnaces are the most common regeneration systems presently in use. Figure 3-7 shows a drawing of a typical multiple hearth furnace system. Figure 3-8 shows a cross-sectional view of the internals of such a furnace. This type of furnace consists of a refractory-lined steel shell containing 5 to 8 circular hearths. Burners are located on the bottom hearth to provide necessary heat for regeneration. Burners can also be located on higher hearths to provide improved temperature profiles for increased performance and flexibility of operation.

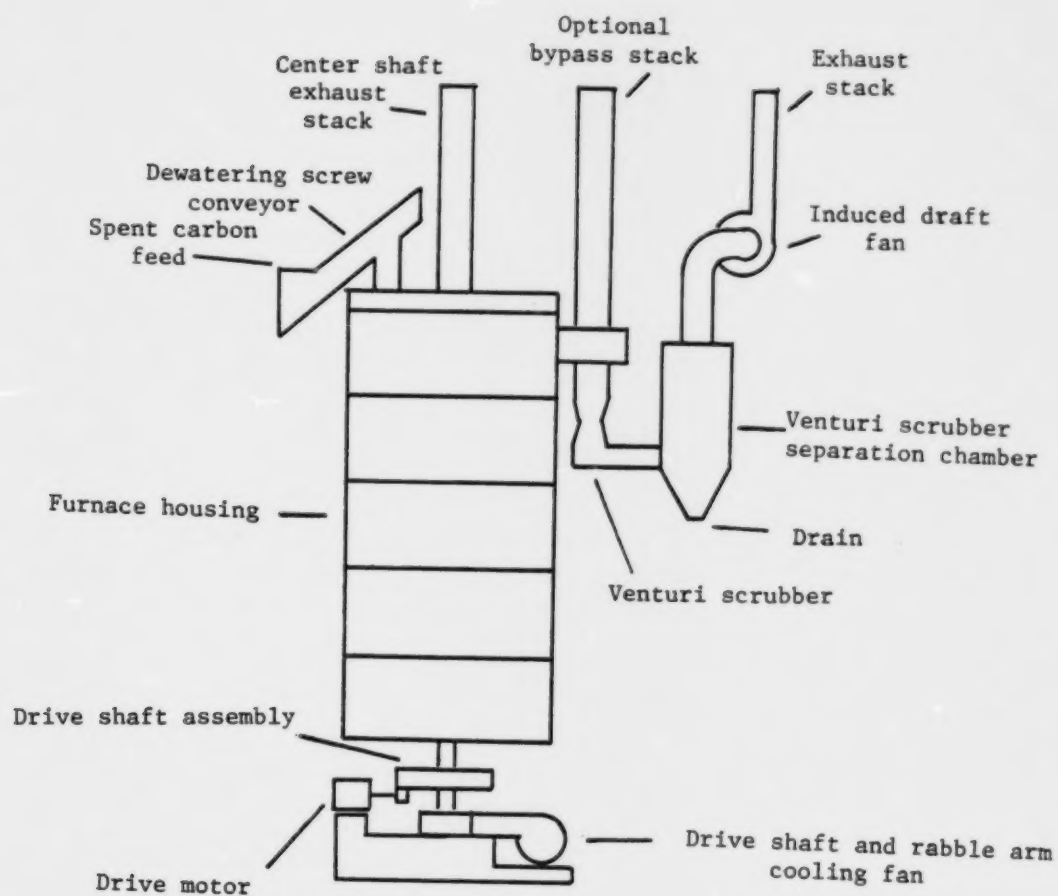


Figure 3-7. Typical multiple hearth furnace regeneration system.

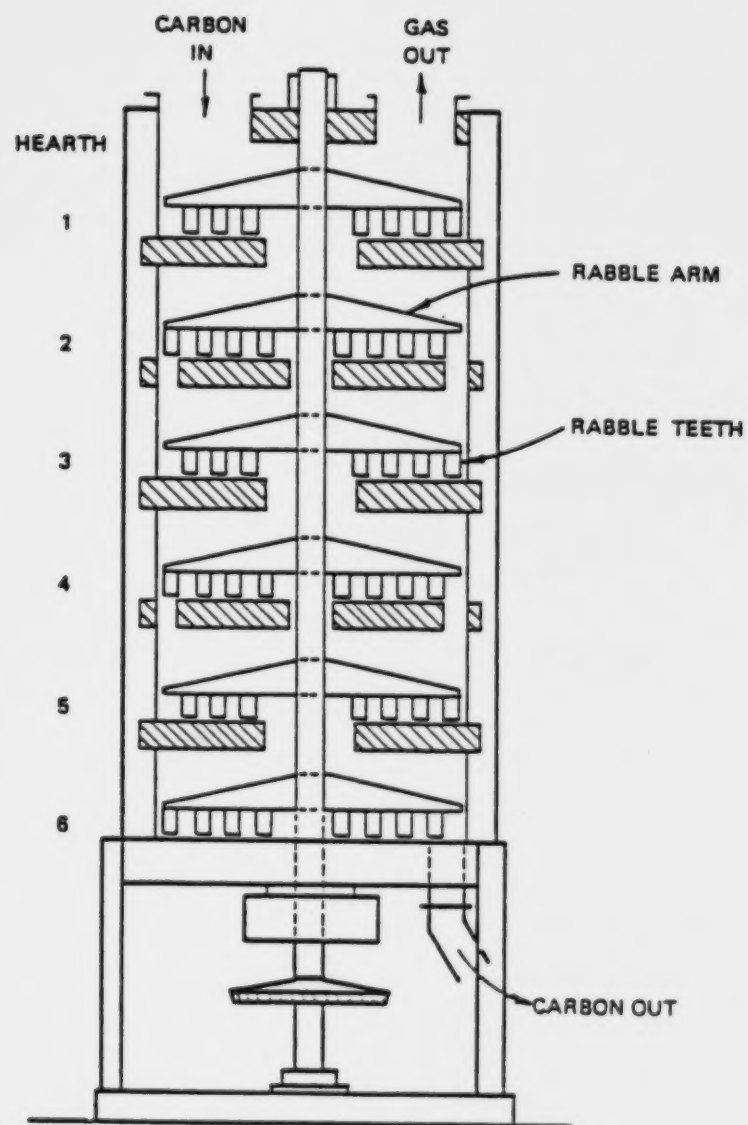


Figure 3-8. Cross-sectional view of multiple hearth furnace.

Source: Reference 23.

Spent carbon enters the top of the furnace through a dewatering screw conveyor onto the top hearth. A rotating center shaft carrying arms with rabble blades moves the carbon in a spiral path so that it drops from hearth-to-hearth and finally out of the bottom of the furnace into a quench tank for cooling. The residence time in the furnace is controlled by the rotation speed of the center shaft. The hollow rabble arms are cooled by ambient air blown through them. The atmosphere within the furnace is tightly controlled to prevent excessive carbon oxidation. Steam is usually added in the lower hearths.

3.4.2 Fluid-Bed Furnaces

A fluid-bed furnace suspends the carbon particles by an upward flowing gas stream. The velocity of the gas is controlled so that the weight of particles in the bed is just balanced by the upward force of the gas. The use of fluid-beds in this application offers the advantages of uniform temperatures within the bed and high heat and mass transfer rates.

One popular fluid-bed design for activated carbon uses two fluid-beds, one above the other. A schematic of the regenerator is shown in Figure 3-9. The dewatered carbon is dried in the first bed which is maintained at 250°-300°F. Steam must be injected to control the temperature.

The carbon leaves the first bed with a moisture content of about 1%. The dried carbon flows by gravity to the bottom bed; the lower bed is maintained at about 1800°F. As the carbon temperature increases to the temperature of the bed, adsorbed organic materials undergo the regeneration steps of pyrolysis and gasification. After leaving the bed, the carbon is cooled in a water-filled quench tank.

Air is injected into the space between the two beds which serves as a second combustion zone. This burns the organic compounds, the H_2 and the CO that are released during regeneration in the lower chamber. Part of the heat produced dries the wet carbon in the upper bed, with the remainder reradiated to the lower bed regeneration zone. The addition of air at this location reduces or eliminates the need for an afterburner and, therefore requires less energy than that required by a multihearth furnace. Since there is no afterburner, the gases leaving the fluid-bed regenerator will be cooler than those produced by multi-hearth furnaces.

3.4.3 Infrared Furnaces

An infrared furnace consists of an insulated enclosure through which the carbon is transported on a continuous metal conveyor belt. The heat for regeneration is supplied to the furnace by a number of electric infrared heating elements mounted in the top of the tunnel.

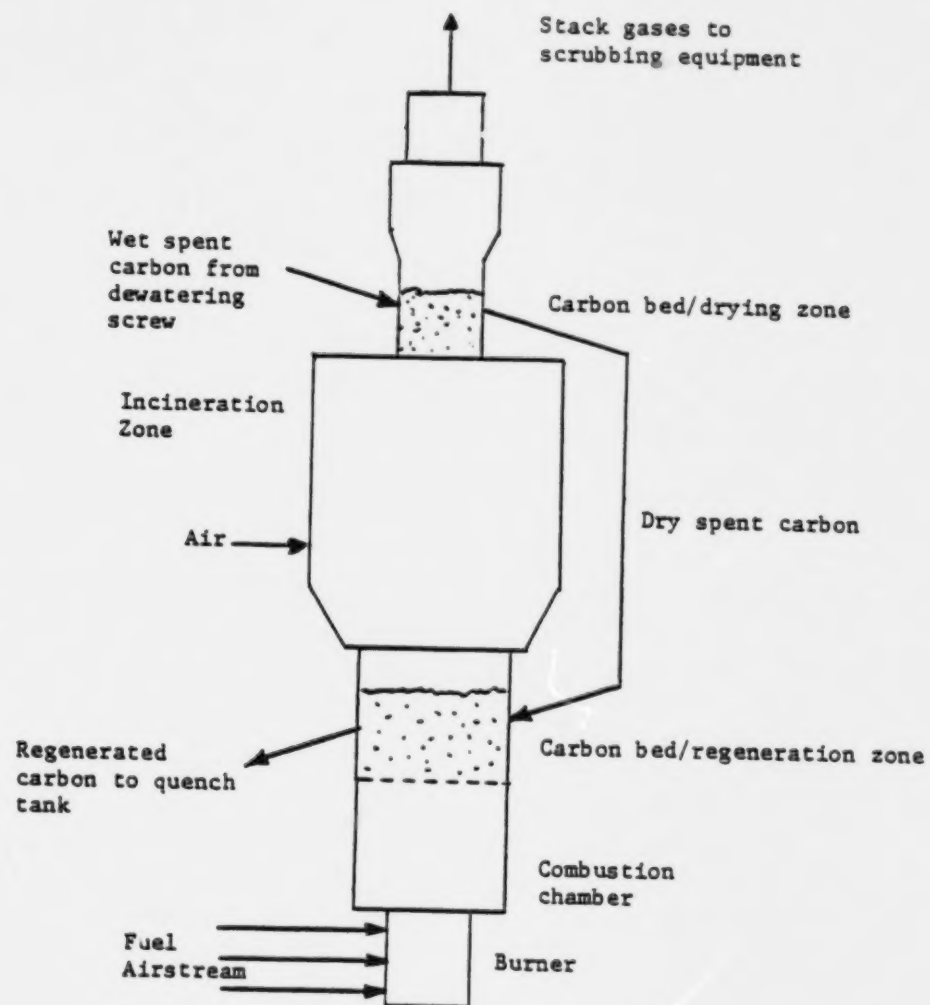


Figure 3-9. Fluidized bed regeneration furnace.

Adapted from Reference 24.

The spent carbon is fed to the regenerator through an air-lock which controls the carbon feed rate and minimizes air intake. The carbon is spread evenly (3/4 to 1 inch depth) onto the belt and transported slowly through discrete chambers or zones of the furnace. The chambers provide increasingly higher temperatures and accomplish the four regeneration stages discussed previously. The atmosphere and temperature can be tightly controlled with this type of furnace. The carbon discharges into a conventional water-filled quench tank for cooling.

Figure 3-10 shows a cross-sectional view of an infrared furnace developed by Shirco, Inc., which is the only company to have commercialized this process to date. The unit is built of standard modules which allow for quick assembly and startup. The modules are made up of a steel shell lined with a thermal shock resistant ceramic fiber blanket insulation and the support rollers for the conveyor belt.

3.5 REGENERATION DESIGN PARAMETERS

3.5.1 Regeneration Rate

The first consideration in the design of a regeneration system is the regeneration rate. This depends on carbon loading and carbon usage or exhaustion rate in the adsorbers. Carbon loading is the quantity of organic substance removed from the water per unit quantity of carbon. Carbon loading is usually expressed in terms of milligrams per gram (mg/g) or pounds per pound (lb/lb) of organic material to carbon. This is not the equilibrium carbon loading determined by isotherm tests; rather, it is the value achieved with a given system under given operating conditions. An increase in carbon loading for the same wastewater and treatment objective lowers regeneration carbon throughput in the furnace due to the longer residence time required to regenerate the carbon. Carbon usage is sometimes expressed as carbon dosage or pounds of carbon per million gallons of water treated. It is inversely related to carbon loading.

Carbon usage rate, or exhaustion rate, is the mass of carbon exhausted per unit time. It is usually expressed as pounds per day (lb/day) and is inversely related to regeneration frequency, which measures how often a given bed of carbon must be regenerated. It is the minimum rate at which carbon would be regenerated in a continuous system with no intermediate storage. In practice, carbon storage is placed between the adsorbers and regenerator so that the furnace sizing is based on higher flow rates of carbon than this minimum value. Operation at the higher rate compensates for furnace downtime while still meeting the carbon usage rate of the adsorbers.

3.5.2 Furnace Size

Furnace design is based on the rate at which carbon is charged per some unit of furnace dimensions. This varies with the type of regeneration furnace chosen. For multiple hearth furnaces, the value is usually given in pounds of carbon per day per square foot of hearth area (lb/ft² day). For multihearth

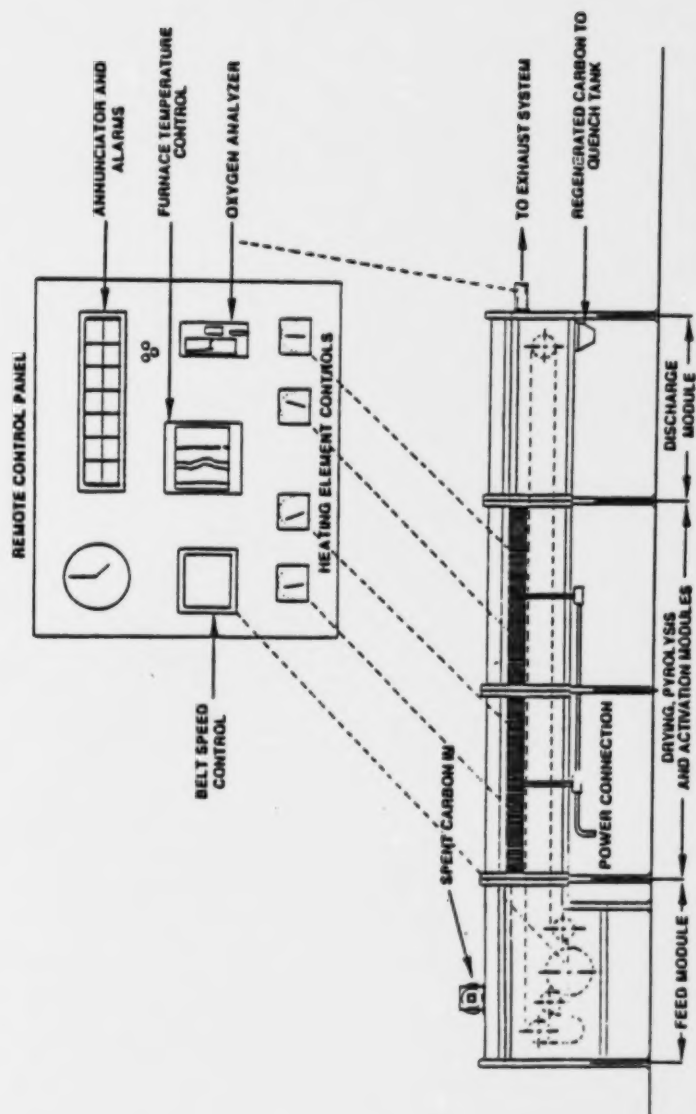


Figure 3-10. Infrared regeneration furnace.

Source: Reference 25.

furnace design, values have been reported in a range of 40 to 115 lb/ft³ day. The values for fluidized bed furnace loadings range from 1460 to 1700 lb/ft³ day. The basis for these numbers is the cross-sectional area perpendicular to the flow of combustion air. In an infrared furnace, the carbon flow depends on the width of the conveyor belt and residence time. Table 3-7 lists typical overall parameters for the three furnace types.

3.5.3 Temperature and Atmosphere Control

Temperature and composition of the vapor space in the furnace are important operating parameters. These two variables influence the amount of carbon that is lost during a regeneration. To minimize carbon loss, it is important to maintain the proper amount of oxygen in the furnace. The oxygen content must be high enough to pyrolyze the char but not so high as to burn the carbon. At a fixed operating air mixture, the temperature must be controlled for the same reasons. There exists a precise, desired temperature profile for each type of GAC. Experience with industrial and municipal wastewater treatment indicates that losses can be held to no more than 8-10 percent per cycle if the adsorptive activity of the regenerated carbon is held to 90 percent of the virgin activity by proper adjustment of furnace variables (18).

3.5.4 Offgases Pollution Control

The offgases resulting from the regeneration process contain potential air pollutants. The most common approach to offgas pollution control is to use an afterburner followed by a wet scrubber. The afterburner oxidizes organic compounds, and the scrubber removes particulate matter and any soluble chemical species from the gas stream.

Many different scrubber designs are used for cleaning regeneration offgas. Water is the usual scrubbing medium. Infrared furnaces require the smallest amount of scrubber water circulation of the furnaces due to the relatively low offgas flow rate. Multi-hearth furnaces probably use the most scrubber water because of the higher offgas temperatures.

A supplementary dust collector is used only where it is necessary to collect particulate matter not normally removed by scrubbers.

3.5.5 Offsite Custom Regeneration

One alternative to regenerating GAC at the plant site is custom offsite regeneration. Spent carbon is shipped to another location where it is batch-regenerated to minimize intermixing with other carbons. The regenerated carbon is then shipped back to the treatment plant for reuse. Currently, offsite regeneration is a contracted service for which the user pays a monthly fee based on the amount of carbon involved.

TABLE 3-7. TYPICAL OVERALL PARAMETERS FOR THREE REGENERATION SYSTEMS

	Multi-Hearth Furnace	Fluidized Bed	Infrared
Furnace loading (lb/day/ft ²)	40 ^a , 75 ^b , 100-115 ^c	1460-1700 ^c	-
Residence time (min)	120-240	10-20	25 ^f
Natural gas fuel (scf/lb C) ^e	3.0-5.5	1.5-2.2	-
Electricity (kwh/lb C) ^e	-	-	1.6
Steam (lb/lb C)	1.0-3.0 ^{a,b,c}	0.4-0.8 ^{a,b,c}	0
Heat Loss (%) ^d	15	9	-
Carbon Losses (%) ^d	5-7	2-5	5 ^f

Compiled from various literature sources unless individual source specifically noted.

^aReference 16.

^bReference 26.

^cReference 27.

^dThese are reported values which reflect operating experience with various systems and may not represent a comparison on a common basis.

^eFuel requirements reported here reflect values reported in the literature based on experience with operating systems. These reported values are a reflection both of the technology and the specific application and should not be used to evaluate the relative merits of the respective regeneration methods without further analysis.

^fReference 16.

3.6 CARBON STORAGE AND TRANSFER

Carbon storage and transfer includes those parts of the granular activated carbon plant associated with:

- fresh carbon receipt, unloading, and transfer to the adsorbers,
- spent carbon removal from the adsorbers and transport to regeneration subsystem, and
- regenerated carbon transport back to the adsorbers.

Commercial granular activated carbon is shipped in one of several ways:

- bags or drums by truck or rail car,
- bulk by truck, and
- bulk by rail car.

The choice of shipment method and design of unloading facilities depend on carbon usage requirements and local shipment economics. In general, however, individual container shipment would be used for only the smallest systems. Carbon vendors use special bulk trucks which discharge a slurry at the plant site. Piping and transfer hoses are part of the truck. When carbon is shipped in bulk by truck or rail car, direct slurry unloading can be used. This can be done through hoses and special connections on the shipment vehicles or from a dry dump station with slurry makeup directly into a storage vessel. The method used will depend on the quantity and frequency of the shipments of fresh carbon to a specific plant. The choice between open or sheltered storage depends on the need for protection from the weather.

The method for transferring fresh carbon into the adsorbers determines the kinds of equipment required. A common method is to prepare a carbon slurry in a makeup tank and transfer the slurry to the adsorbers when required. The quantity and frequency required for each carbon slurry batch depends on the makeup carbon needs of the specific installation.

Spent carbon is discharged from the adsorbers as a slurry and usually travels to a spent carbon storage tank rather than directly to the regeneration subsystem. Likewise, after regeneration, the carbon returns as a slurry to a regenerated carbon storage tank prior to returning to the adsorbers.

Hydraulic transfer of the carbon slurry is accomplished by one of three devices, an eductor, slurry pump, or blowcase. Eductors are standard vendor-supplied items. A centrifugal pump supplies motive water to the eductor venturi. The slurry is drawn into the venturi by pressure differential, is mixed with motive water, and is moved down the pipeline.

Slurry pumps are centrifugal pumps with solids-handling open impellers. Details of these pumps vary according to manufacturer.

Blowcases are a standard transfer method with one manufacturer's pulse-bed systems (24). Blowcases are small pressure vessels into which a carbon slurry may be transferred by some other method. The blowcase is pressurized with compressed air which forces the carbon slurry into the outlet line leading to the transfer destination.

Spent carbon is typically transported in a concentration of up to three pounds of carbon per gallon of water (16). This concentration permits the use of slurry pumps, avoids eductor plugging, and minimizes pressure drop, pipe size, and attrition losses. Attrition losses occur when carbon abrasion between particles generates fines which are removed from the system during backwash or regeneration.

3.7 MATERIALS OF CONSTRUCTION

Materials of construction for granular activated carbon plants vary. Steel, concrete, or fiberglass are used for vessels, and steel, plastic, or fiberglass for piping. Individual influent stream characteristics and carbon used determine construction material requirements.

Dry carbon and carbon in water slurries are not corrosive. Damp carbon, however, is extremely corrosive (28). To overcome this corrosivity, all metal that will be in contact with damp carbon has to be corrosion-resistant.

Steel adsorbers are usually made of carbon steel coated with rubber, epoxy, or other materials. It has also been suggested that steel tanks can be protected by a cathodic protection system (16). Solid stainless clad carbon steel may be useful, especially for industrial systems. Fiberglass vessels are another option for overcoming the corrosion problem. Corrosion problems do not occur with concrete vessels except for metal parts such as nozzles, screens, piping and weirs.

Piping can be either carbon steel or stainless steel depending on its location and purpose in the system. As with vessels, various linings can be used for piping. Valves and instruments such as flow meters must be of materials compatible with the potential for corrosion in their respective parts of the system. It has been suggested that using carbon steel with periodic replacement might be less costly than stainless steel construction (16). Plastic or fiberglass piping offers another alternative where corrosion problems are anticipated.

In the regeneration systems, both carbon steel and stainless steel are used for various equipment components. Furnaces are usually carbon steel with refractory liners. Certain furnace components in contact with damp carbon or exposed to high temperatures are made of stainless steel. (The dewatering feed screw and quench tank are examples of such items).

3.8 PRETREATMENT AND POST-TREATMENT

Successful application of granular activated carbon requires the removal from the influent stream of excessive contaminants such as suspended solids, oils, and greases. The sensitivity of the adsorption of certain materials to pH might require pH adjustment. Problems with bacterial growth in carbon beds (septicity) which have sometimes been encountered in biologically active wastewaters might necessitate disinfection. Finally, flow equalization can be used to even out fluctuations in influent flow rate and properties, thereby enhancing system performance.

Pretreatment practices depend on the application area. Usually, in drinking water or municipal wastewater treatment, the influent water to carbon adsorption has been filtered through granular media filters. This might also be the case for some industrial wastewaters, but it is more likely that some industrial wastewaters will not be filtered prior to carbon adsorption. In general, suspended solids concentrations should be about 60 mg/l or less, and oil content should be less than 20 mg/l (29) to prevent blinding the active pores of the carbon.

3.9 APPLICATIONS AND PERFORMANCE

As stated earlier, activated carbon is used in the treatment of both drinking water and wastewater. Performance of granular activated carbon systems in these applications is evaluated by the percentage removal of contaminant from the water streams and by the carbon usage rate required to achieve the contaminant removal. Removal efficiency depends on the major adsorber design parameters of contact time, carbon type, and influent stream characteristics. For a given adsorber design configuration, the carbon usage rate depends on the physical-chemical interaction between the adsorbate or stream contaminant and the carbon. Different kinds of organic compounds have different adsorption characteristics which lead to different performance behavior in a granular activated carbon system. Very low and very high molecular weight species are poorly adsorbed. Aromatics, non-polar, and poorly water soluble materials are amenable to adsorption by activated carbon.

3.9.1 Drinking Water

Historically, activated carbon has been used for taste and odor removal. With the passage of the Safe Drinking Water Act in 1974, however, activated carbon was recognized as a method of removing synthetic organic chemical contaminants in water supplies.

Table 3-8 summarizes proposed maximum concentration levels for some organic chemicals in drinking water supplies (30).

The U.S. Environmental Protection Agency has encouraged, conducted, and sponsored research to evaluate granular activated carbon performance for these uses. The primary differences between the historical application and the new

TABLE 3-8. PROPOSED MAXIMUM CONCENTRATION LEVELS (MCL) OF SOME SYNTHETIC ORGANIC CHEMICALS (PESTICIDES) IN DRINKING WATER (30)

Contaminant	Maximum Contaminant Level
Endrin	0.002 mg/l
Lindane	0.004 mg/l
Toxaphene	0.005 mg/l
2, 4-Dichlorophenoxyacetic acid (2,4-D)	0.01 mg/l
2, 4, 5-TP (Silvex; (a derivative of 2,4,5-Trichlorophenoxyacetic acid)	0.01 mg/l
Methoxychlor	0.1 mg/l
Trihalomethanes and organic chemicals ^a	-

^aOn February 9, 1978, the EPA proposed to amend the National Interim Primary Drinking Water Regulations by adding regulations for restricting trihalomethanes in drinking water. The proposed amendment is as follows:

An MCL of 0.10 mg/l (100 parts per billion) for total trihalomethanes (THM), including chloroform.

use are in the depth of the carbon beds required, and in the increased regeneration requirement. Plants using carbon only for taste and odor removal required bed depths of up to about 2 feet. Plants using carbon for the new applications require beds of greater depths depending on influent contaminant concentrations and characteristics. Also, whereas the carbon usage rate for taste and odor removal is low and a bed remains in place for a year or more, regeneration might be required several times a year in the new application.

A list of plants using carbon for taste and odor removal was compiled in an earlier publication (18). Plants with granular activated carbon systems for the new application are listed in Table 3-9.

Two procedures are possible for using GAC as the adsorption medium, depending on whether or not it is being retrofitted to an existing plant. In an existing plant, GAC can be used as a replacement for the filter media in existing filter beds (sand replacement). Or, it can be used in separate vessels after filtration (post-filter adsorption). Only post-filter adsorption is considered in this report.

TABLE 3-9. EPA-SPONSORED DRINKING WATER GAC DEMONSTRATION AND PILOT PLANTS FOR ORGANICS CONTAMINATION REMOVAL^a

Location	Year Installed	Plant Size (mgd)	Hydraulic Loading (gpm/ft ²)	Bed Depth (ft)	EBCT ^b (min)
Manchester, N.H.	1979	15	3.0	4	10
Passaic, N.J.	1979	2.2	-	-	-
Cincinnati, Ohio ^c	1980	4	6.2	15	18
Queensburg, N.Y.	No data available.				
Amesburg, Mass.					

^aThere are far more plants designed for taste and odor removal which are not listed here. A list from the American Water Works Association was published in Reference (18).

^bEBCT = empty bed contact time.

^cDesign parameters are estimates.

Synthetic organic chemicals are routinely removed by GAC in the treatment of industrial wastewaters. In drinking water applications, the concentrations of organic compounds can be expected to be much lower. Although GAC is capable of removing low concentrations of organic materials it may be very costly in this application where very low effluent requirements mandate high carbon usage rates.

For synthetic organic chemicals, the maximum concentration limit varies by compound or class of compound. These criteria were listed for several toxic substances in Table 3-8. Regeneration conditions for this application must be established.

The type of adsorption system selected depends both on plant volume and performance considerations. Small plants can effectively use lined carbon steel vessels. Larger plants would use concrete gravity flow adsorbers. For drinking water, downflow is considered essential to prevent carbon fines from being carried into the drinking water supply (18).

3.9.2 Municipal Wastewaters

The first application of GAC to municipal wastewater treatment was at South Lake Tahoe, California. The plant began operation in 1968. Other

GAC installations were subsequently built in different parts of the country. Table 3-10 lists municipal wastewater granulated activated carbon installations. Table 3-11 lists design and performance data for plants on which data are available.

In municipal wastewater treatment, the objective has been to reduce effluent biochemical oxygen demand, (BODs), and chemical oxygen demand, (COD), to levels below those that can be achieved by conventional treatment methods. Granular activated carbon is an add-on process step to other steps in a total treatment plant.

Two fundamental approaches have been used in municipal wastewater treatment plants. In physical chemical treatment (PCT), the granular activated carbon treatment is the primary method for organics removal. It follows process steps for suspended solids removal. The other approach, advanced wastewater treatment, (AWT)^a, employs activated carbon after both solids removal and biological treatment for organics removal. It serves more as a polishing step than as a primary removal step.

Conventional biological wastewater treatment processes remove a high percentage of biodegradable organic compounds by biological oxidation. They are not as effective in removing refractory organic compounds measured by a COD test. Refractory organic compounds include tannins, lignins, ethers, some proteinaceous materials, color and odor producing materials, herbicides, pesticides, and materials classified as methylene blue active substances (MBAS) (2).

3.9.3 Industrial Wastewaters

The characteristics of industrial wastewaters are extremely diverse. Table 3-12 lists industrial categories for which wastewater treatment is a major requirement. Even within each category, the site-specific characteristics vary widely. The total number of industrial activated carbon installations is not precisely known at this time but has been reported as being in excess of 100.

^aSometimes this is also referred to as tertiary treatment.

TABLE 3-10. MUNICIPAL WASTEWATER PLANTS USING GRANULAR ACTIVATED CARBON^a

-
1. South Tahoe (CA), Public Utility District
 2. Tahoe - Truckee (CA), Sanitation District
 3. Upper Occoquan (VA), Sewage Authority
 4. Vallejo (CA), Sanitation and Flood Control District
 5. Orange County (CA), Water District
 6. Niagara Falls (NY), City of
 7. Fitchburg (MA), City of
 8. LeRoy (NY), Village of
 9. Colorado Springs (CO), Municipal Wastewater Treatment
 10. Trinity River Authority, Grand Prairie (DALLAS), Texas
 11. Fairfax County (VA)
 12. Los Angeles (CA), City of
 13. Montgomery County (MD)
 14. Piscataway (MD)
 15. St. Charles (MO)
 16. Pomona (CA)
 17. Rocky River (OH)
 18. Derry Township (PA)
 19. Santa Clara V.W.D. (CA)
 20. North Tonawanda (NY)
 21. Nassau County (NY)
 22. Arlington County (VA)
 23. Courtland (NY)
 24. Washington (DC), Suburban Sanitation Commission
 25. Westerly Plant (Cleveland, OH)
 26. Garland (TX), City of
 27. Owosso (MI)
 28. Rosemont (MN)
 29. Ocean Beach (NY)
 30. Sylvan Beach (NY)
 31. Alexandria (VA)
 32. Aquia (VA)
 33. Waterville Valley (NH)
 34. Cedar Creek (NY)
-

^aCompiled from various sources throughout the literature.

TABLE 3-11. PERFORMANCE AND DESIGN DATA FOR SELECTED MUNICIPAL WASTEWATER PLANTS^a

Municipal Wastewater Plant	Capacity mgd.	Type	Contractors		Size(ft)	Contact Time, min.	Performance		
			Number	In Series			Influent Concentration mg/l	Effluent Concentration mg/lg	% Removal
South Tahoe, CA	7.5	Upflow packed	8	1	12 x 14.5	17	BOD - 3 COD -25	0.7 10	70 60
Tahoe - Truckee, CA	4.8	Upflow packed	6		12 x 20	20	COD -26	15	42
Upper Occoguan, VA	15.0	Upflow packed	16	1	12 x 24.3	22	-	BOD - 1.0 COD -10.0	-
Vallejo, CA	13.0	Upflow expanded	6	1	18x18x16 deep	-	BOD -104 COD -175	45 90	57 49
Orange County, CA	15.0	Downflow	17	1	12	34	COD -42 TOC -14.4	16.6 7.0	60 51
Fitchburg, MA	15.0	Downflow pressure	12	1	20 x 15.5	15	COD -53.4 BOD -13.2	6.8 1.7	87 87
Colorado Springs, CO	3.0	Downflow	3	2	20 x 8	17	COD -57 BOD -27 TOC -24	31 13 10	46 52 58

^aCompiled from information in various sources throughout the literature.

TABLE 3-12. MAJOR INDUSTRIAL CATEGORIES FOR WASTEWATERS

Auto and Other Laundries
Coal Mining
Electroplating
Inorganic Chemicals Manufacturing
Iron and Steel Manufacturing
Leather Tanning and Finishing
Machinery and Mechanical Products
 Aluminum Forming
 Battery Manufacturing
 Coil Coating
 Copper Forming
 Electrical and Electronic Components
 Foundries
 Mechanical Products
 Photographic Equipment and Supplies
 Plastics Processing
 Porcelain Enameling
Miscellaneous
 Adhesives and Sealants
 Explosives Manufacture
 Gum and Wood Chemicals
 Pesticide Manufacturing
 Pharmaceutical Manufacturing
Nonferrous Metals Manufacturing
Ore Mining and Dressing
Organic Chemicals Manufacturing
Paint and Ink Formulation
Petroleum Refining
Plastic and Synthetic Materials Manufacturing
Pulp and Paperboard Mills and Converted Products
Rubber Processing
Soap and Detergent Manufacturing
Steam Electric Power Plants
Textile Mills
Timber Products Processing
Food Processing

Source: Reference 32.

Known industrial groupings of wastewater installations using GAC are listed in Table 3-13, along with some system parameters. For industrial wastes, performance criteria are measured by BOD₅, COD, TOC (total organic carbon), and specific chemical compound concentrations.

Prominent uses of granular activated carbon include:

- phenolic compound removal in refinery and chemical process streams, and
- pesticide and herbicide removal in their process wastewaters.

One must exercise caution when interpreting reported performance data. Sometimes the reported removal efficiency applies to the overall treatment system of which GAC is only a part. In other reports the influent and effluent characteristics of the GAC system alone are given. This information allows calculation of GAC removal efficiency alone.

3.9.4 Granular Activated Carbon and Chemical Waste Dump Cleanup

A further application of GAC adsorption is for leachate and contaminated surface water cleanup at currently uncontrolled chemical waste dumps. GAC systems in this application are likely to be in the range of tens of thousands to perhaps a few mgd. These systems represent the lower end of the range of GAC system capacities.

Another characteristic of these systems is that their installation and operation is often temporary. In addition, their installation and startup is frequently required within a relatively short time frame. While custom built systems could be used, it is more likely that skid-mounted packaged systems would be preferable for these applications.

Because these systems are small, on-site regeneration may not be feasible. Multi-hearth furnaces are not generally considered economical when carbon regeneration requirements are less than 1000 lb/day. It is possible that small fluid bed or infrared furnaces could meet low throughput regeneration requirements. Their feasibility has not been fully evaluated in this application, however. A current practice in this application is to contract for an off-site regeneration service, or to contract for both an adsorption system and off-site regeneration. Location will influence the approach which is suitable in a specific instance.

In this report, the costs of GAC for chemical waste cleanup application can be estimated using the same methods used for larger systems. However, the carbon adsorber costs for packaged systems should be used for the low ranges of flow rates. Costs for other system components can be estimated as required for the smaller size ranges.

Design considerations for these systems must take a number of variables into account. Pretreatment requirements may be more difficult due to the

TABLE 3-13. SOME EXAMPLE GAC INDUSTRIAL WASTEWATER DATA^a

SIC Code	Industrial Category	Contaminant				EBCT min.	Carbon Dosage lb/1000 gal.
		Phenol		TOC			
		In mg/l	Out mg/l	In lb/lb ^c	In mg/l	Out mg/l	1b/lb ^c to 0.44
286	Industrial Organic Chemicals	4-420	0.1-21.4	0.004 to 0.167	203-79,800	42-66,700	0.04 to 0.44
287	Pesticides	2.8-137	0.7-4.3	0.03	689-79,800	15.4-66,700	0.01
282	Plastics	15	.1	0.009	-	-	-
2911	Refinery	1.9-32	0.7-15.1	-	122	71	0.36
2899	Specialty Organics	26.6	1.3	-	7,323	-	-
2892	Explosives	-	-	-	13.1	5.9	0.08
2272	Textiles	-	-	-	62.6-150	5-5.5	0.08
283	Drugs	52	.69	-	600	48	-
2999	Coke Products	-	-	-	-	-	-
							116
							35

^aCompiled from information on individual installations in References 32, 33, 34, 35, 36, 37.^cSIC = Standard Industrial Classification, a system used by the U.S. Department of Commerce for categorizing industries.^cTOC = total organic carbon.^dEBCT = empty bed contact time.

random complexity of the influent stream. Depending on if and how equalization might be employed, the composition and concentrations of materials in the feed stream can be expected to fluctuate to a greater extent than in the other application areas. There is probably an increased potential for both occlusive preferential adsorption as well as chromatographic displacement effects. In addition, the concentration of organics might vary over a much wider range than in other applications.

3.9.5 Influent Water Characterization

The performance of any GAC treatment system depends on individual surface phenomena, and is sensitive to trace materials present. Also, adsorption of individual compounds differs in mixtures and in pure components to such an extent that phenomena such as selectivity, displacement, and chromatographic separations can occur. In evaluating activated carbon treatment, influent water characterization is important.

In the typical characterization of any influent water, GAC performance is measured by one of or all of the following: BOD₅, COD, TOC, or specific chemical compounds or classes of compounds (e.g., phenol; trihalomethanes). Different criteria are applied in different application areas. Historically, there has not been consistency in any one application area due to site-specific needs being addressed at the time a particular study was conducted.

In general, COD, TOC, and specific contaminant designations have been used for the drinking water and industrial wastewater areas, and BOD₅, COD, and TOC for municipal wastewaters.

Other influent water characteristics are used in system design. For example, pH adjustment might be required to obtain optimum performance in a given system. In general, removal efficiency increases as pH decreases. Another example of how the influent analysis can affect design is that problems with stainless steel can be anticipated if chloride content is too high.

The variability of individual streams selected for treatment is the reason pilot testing is usually recommended to develop a data base for designing a full-scale facility.

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SECTION 4

MODULAR COST DATA

This section presents cost data for process modules that comprise granular activated carbon systems. There are several subsections grouping modules according to the subsystem to which they belong.

For each process module there is a brief discussion of major design specifications and operating requirements, a schematic drawing, and graphs of cost data. Capital costs are presented as direct capital cost, and operating costs as processing expenses. These cost elements correspond to Items 11 and 70 defined by Uhl (1) as was shown in Table 2-2 and 2-3 of Section 2. For each module, costs are plotted against an appropriate capacity variable. For example, carbon adsorber costs are plotted against adsorber volume in cubic feet (ft³). Regeneration furnace costs are plotted against carbon throughput rate in pounds per day (lb/day).

Direct capital costs are factored estimates based on purchased equipment costs obtained from or developed from information in literature sources. Factors account for the following items associated with equipment installation:

- piping
- structural steel
- foundations (concrete work)
- electrical accessories
- instrumentation,
- painting, and
- installation labor

Specific factors used are discussed in the Appendices to this report.

Processing expenses cover the costs of operating, maintenance, and supervisory labor, maintenance materials, electrical power, fuel, carbon losses, and other minor items such as compressed air, and operating materials. Processing expenses are based on operating requirements and prices obtained from or developed from literature sources.

Methods for combining modular costs of this section into system costs are discussed and illustrated by example in Section 5. Fundamentally, all the user needs to do is to select the appropriate size and number of modules for the specific carbon system design of interest and add up the costs. Then certain factors must be applied and additional costs added to arrive at the total capital investment and total annual cost for any given system.

The subsystems into which process modules are grouped are:

- carbon storage and transfer,
- adsorption,
- regeneration, and
- auxiliary equipment and offsites.

These are discussed below.

4.1 CARBON STORAGE AND TRANSFER SUBSYSTEM

Process modules which comprise the carbon storage and transfer subsystem include: fresh carbon storage and transfer, spent carbon storage and transfer, and regenerated carbon storage and transfer.

Fresh carbon for GAC systems is received in bulk by truck or rail car or in shipping containers such as bags or drums. Costs presented in this section cover storage of the fresh carbon on-site in a storage vessel and equipment for transfer of fresh carbon to the adsorbers. After initial startup of a GAC system fresh carbon is periodically required to compensate for carbon losses.

When carbon in the adsorbers is exhausted, it is discharged from the adsorbers and transferred to spent carbon storage prior to regeneration. After regeneration, carbon is again stored prior to transfer back to the adsorbers.

Several methods used for transferring carbon as a water slurry between vessels discussed in Section 3 were the eductor, pump, or blowcase.

These methods are illustrated conceptually in Figure 4-1.

Each of these methods was examined for developing the module costs that follow. In estimating costs for carbon storage it was found that cost differences among the three transfer methods, and the three types of storage at the same storage volume, were relatively small. Therefore, only one set of cost curves is presented which applies to all three storage modules.

Types of vessels used for the storage of fresh, spent, and regenerated carbon are assumed to be identical. Piping arrangements, however, are specific to each of the three types of storage.

For manual loading and storage of fresh carbon, the only equipment items might be a storage shed and equipment for handling pallets of containerized carbon. These equipment items are such a small portion of total plant costs that they are well within any contingency allowance used in preparing the cost estimates and are not explicitly computed.

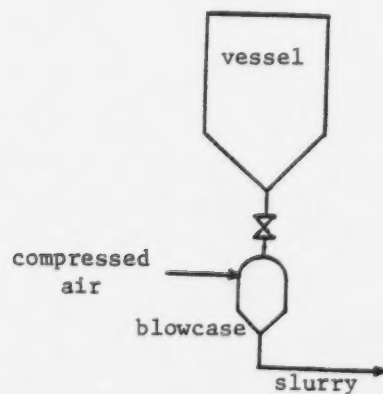
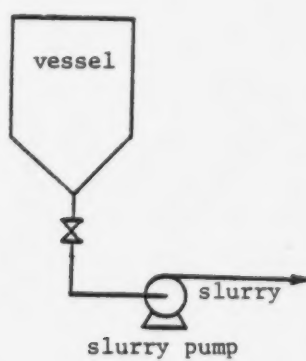
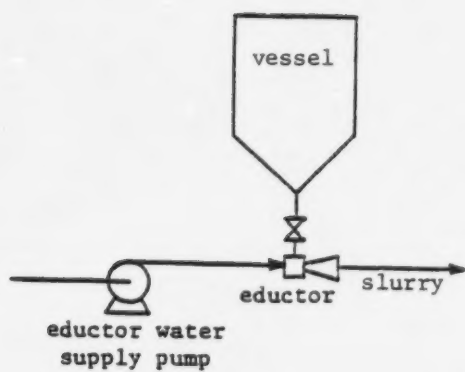


Figure 4-1. Carbon storage and transfer options.

Large quantities of carbon unloaded dry or by slurry would be charged to a storage silo or tank. A typical fresh carbon unloading and storage facility might consist of only the tank in a case where the carbon was delivered in trucks self-equipped for slurrying the carbon. Or it might be a dry dump and slurry makeup station used for bulk rail car delivery.

Spent carbon storage receives a carbon slurry from a discharging adsorber. Spent carbon storage discharges a carbon slurry to the regeneration system. The reverse is true for regenerated carbon storage.

Design Basis

Storage Tank--A carbon steel or stainless steel cylindrical storage tank with a flat top and conical bottom is used. The tank discharges through a valve into the slurry eductor, inlet to a slurry pump, or into a blowcase.

Slurry Eductor--A carbon steel or stainless steel eductor is permanently installed directly under the storage tank.

Piping and Valves--Slurry piping is schedule 40 carbon steel or stainless steel. Piping is sized for a 25% slurry of carbon in water. Valve types can vary. For costing purposes, manual gate valves rated for 150 psig are used.

Eductor Water Supply Pump--The pump to supply water flow to the eductor is a standard general purpose electrically-driven carbon steel centrifugal pump. One pump is shared by all eductors in a system since they will not all operate simultaneously.

Carbon Slurry Transfer Pump(s)--The pump(s) for direct slurry pumping will be specifically designed for slurry service. For costing purposes, however, general purpose electrically-driven carbon steel centrifugal pumps are used. A storage module contains one operating pump with one spare.

Direct Capital Cost

Direct capital costs are given in Figure 4-2 for storage with either stainless steel or carbon steel vessels.

Operating Requirements

Labor--Estimates are based on at least one person full-time during carbon transfer operations. The total hours per year required for transfer depend on both regeneration rate and the amount of carbon losses.

Maintenance Materials--2 percent of direct capital cost.

Power--.007 kW/lb/min of wet carbon in the slurry for slurry pumping based on a slurry concentration of 25 percent carbon, a rate of 70 gpm, and a 50 ft. head. For an eductor system this requirement is about 12 to 20 times

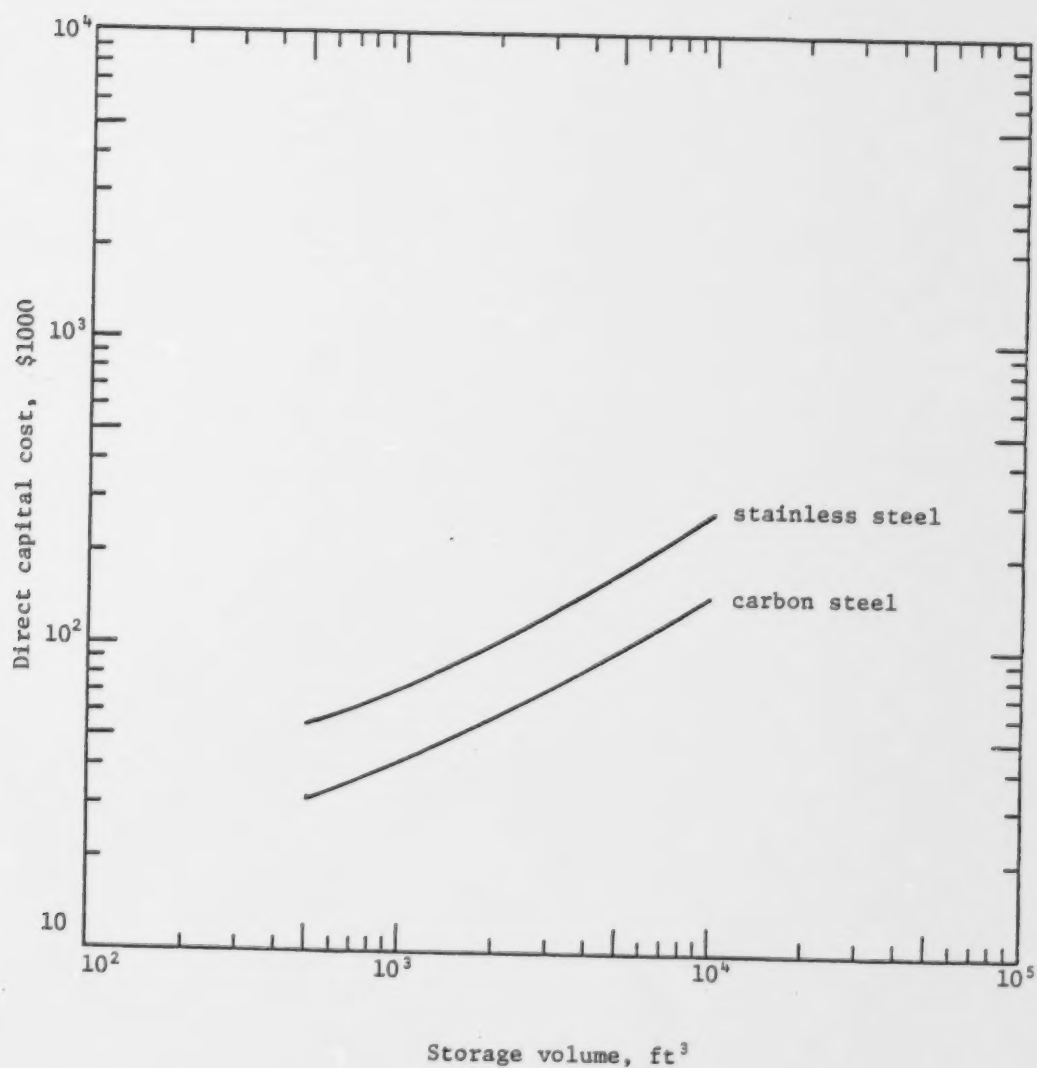


Figure 4-2. Carbon storage and transfer - direct capital cost.
(September, 1980 dollars)

higher. An eductor requires a higher total flow rate because it uses a water stream to move the carbon slurry stream which increases total flow, and it requires a higher head. The flow ratio is from 3 to 5 and the head ratio about 4.

Processing Expenses

Processing expenses are given in Figure 4-3. Due primarily to power costs, these expenses depend on average amount of carbon transferred per day.

Cost References

Costs for components comprising the fresh carbon storage and transfer module were obtained from the following references:

Storage vessels (2); eductor (3); piping and valves (4); pumps (4).

4.2 ADSORBER SUBSYSTEM

Process modules which comprise the adsorber subsystem include:

- adsorbers,
- backwash equipment,
- surface wash equipment, and
- initial carbon charge.

A brief discussion of each module is followed by cost details.

4.2.1 Adsorbers

The basic types of adsorbers were discussed in Section 3 of this report. Process module descriptions and costs in this section cover concrete adsorbers, steel pressure flow adsorbers, steel gravity flow adsorbers, and steel pulsed-bed adsorbers.

Capital costs are presented for adsorbers as individual vessels with associated piping and other capital items as listed on page 8. Adsorber costs are based on standard diameter steel vessels or standard rectangular cross-section concrete vessels with varying heights. Differences in costs occur at the same volume, however, with different materials of construction (e.g. stainless steel vs. carbon steel), different piping complexity (backwash provisions vs. no backwash provisions) for pressure steel vessels, and with vessel diameter.

When multiple adsorbers are required for series or parallel flow systems, individual adsorber costs are multiplied by the number of individual vessels.

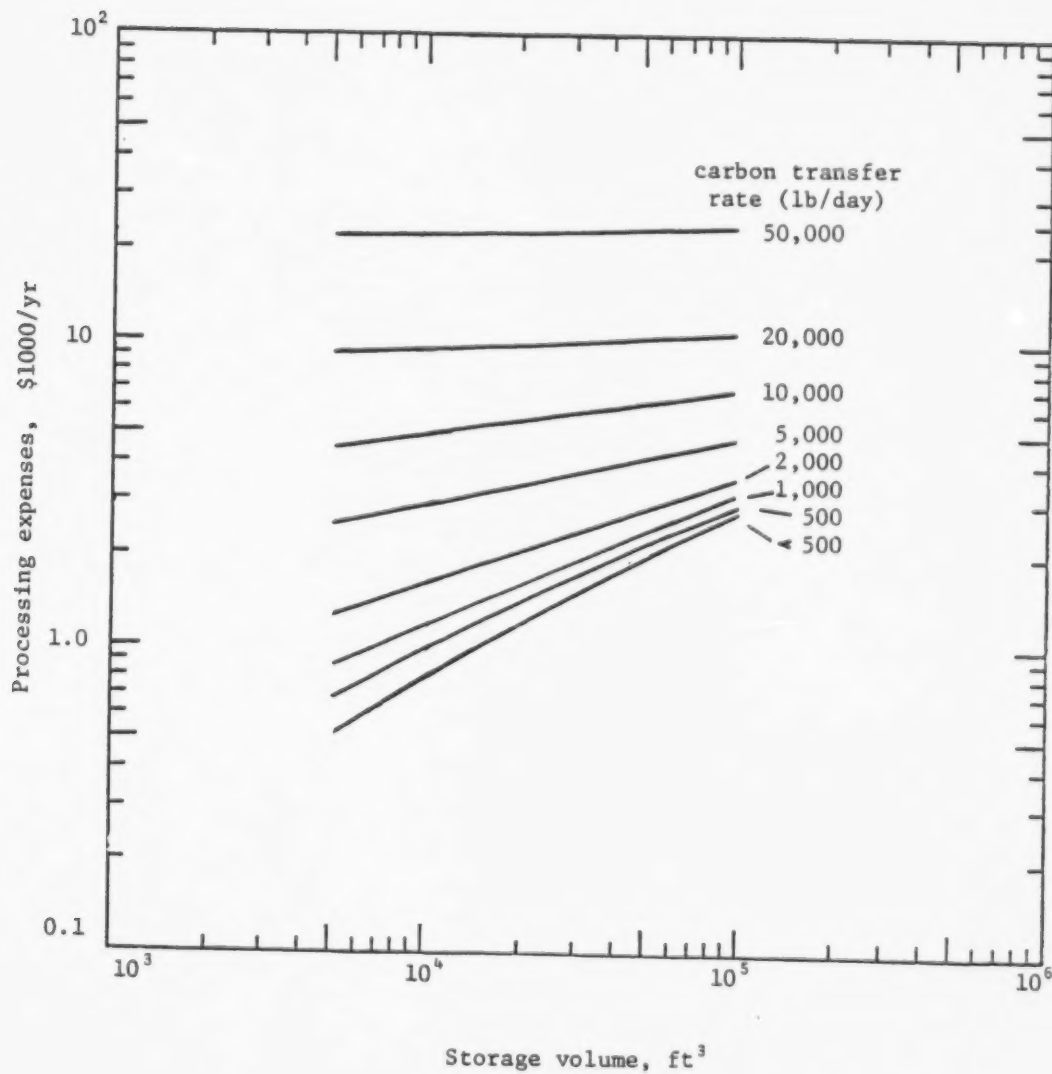


Figure 4-3. Carbon storage and transfer - processing expenses.
(September, 1980 dollars)

Processing expenses are presented differently from direct capital costs. These expenses are not as dependent on volume as on total adsorber area (whether single or multiple vessels are used). Consequently, processing expenses are not provided on an individual vessel basis but as a function of total adsorber area.

Concrete Adsorbers

Design Basis

Several conceptual designs for concrete adsorbers are illustrated in Figures 4-4 through 4-8.

Concrete Structure—The concrete structure consists of reinforced concrete with 12 inch walls on an 18 inch slab foundation. A standard vessel cell has a rectangular cross-section with a length-to-width ratio of 2 to 1. Depths range from 10 to 30 ft.

Vessels include bed support internals as well as influent and effluent liquid and carbon slurry distributors and collectors.

Two designs were included based on actual systems. These designs, referred to as complex and simple, differ in the details of the concrete structural work.

Piping Headers and Valves—Piping for liquid or carbon slurry is Schedule 40 carbon steel or 316 stainless steel. For costing purposes valves are manual gate valves with a 150 psig rating. Some valves in actual systems will be automatic.

Instrumentation—Instrumentation would include level sensors, flow meters, and automatic valve controls.

Direct Capital Cost

Direct capital costs are given in Figure 4-9. Two curves illustrate the different costs that result from the simple compared to the complex design.

Operating Requirements

Labor—Labor requirements are based on the total adsorber area.

Maintenance Materials—1 percent of direct capital cost.

Processing Expenses

Processing expenses are given in Figure 4-10.

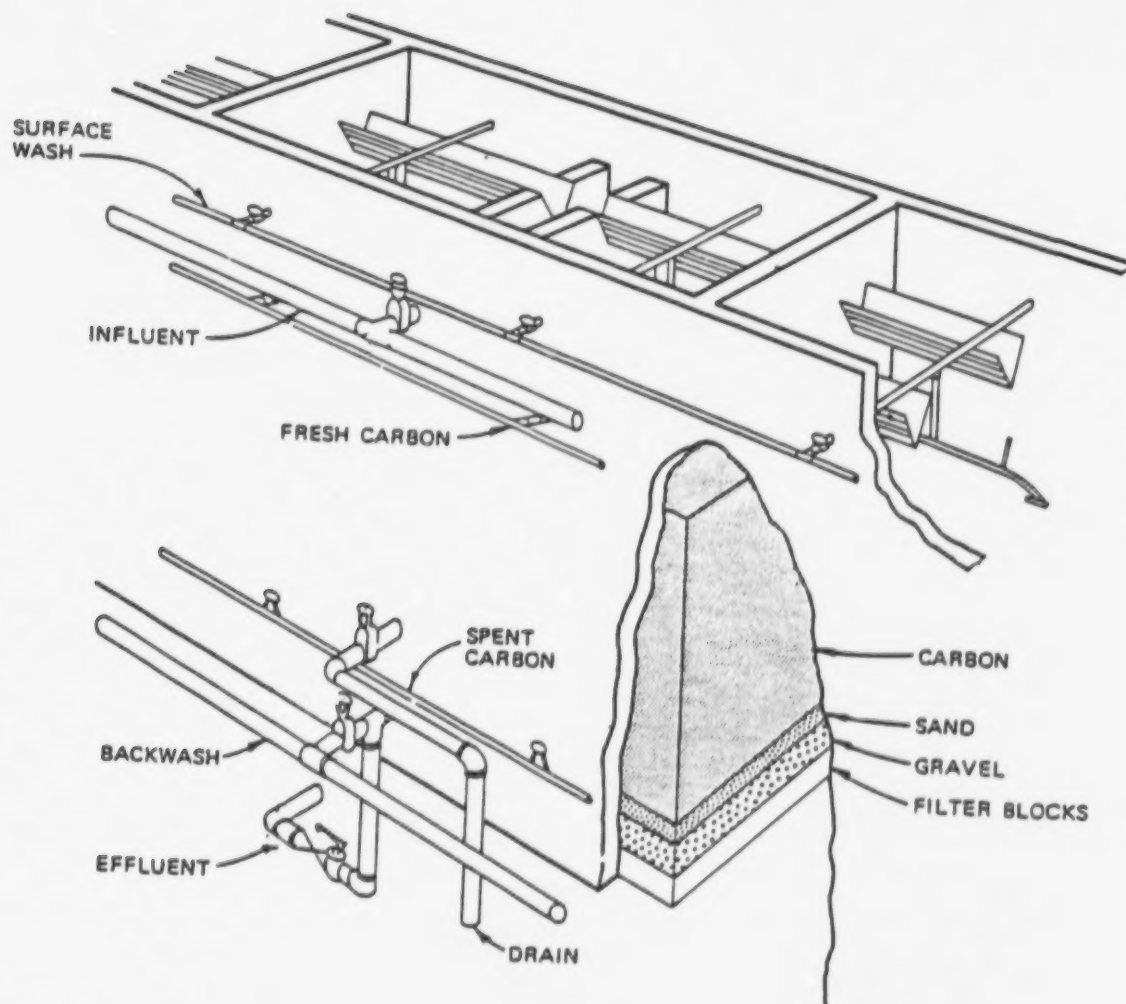


Figure 4-4. Typical concrete gravity downflow adsorber with effluent troughs and external piping.

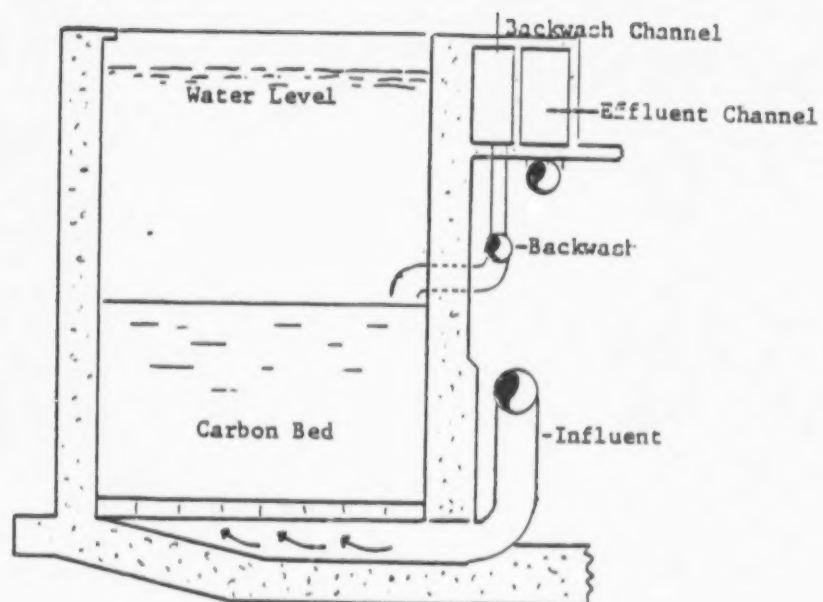
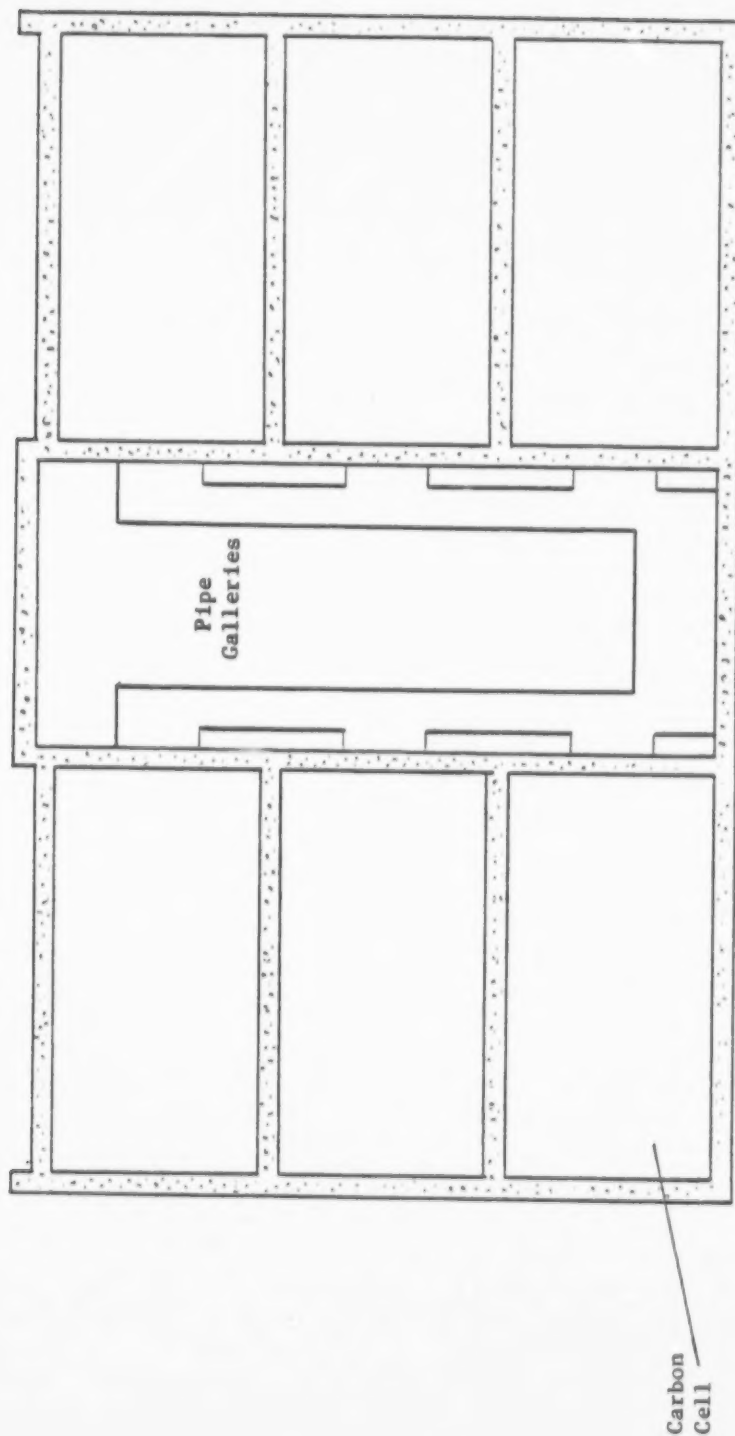


Figure 4-5. Section of concrete adsorber (simple design), with concrete backwash and effluent channels.



Contains Influent, Effluent,
Backwash, and Carbon Transfer Piping

Figure 4-6. Partial plan of concrete adsorbers (simple design).

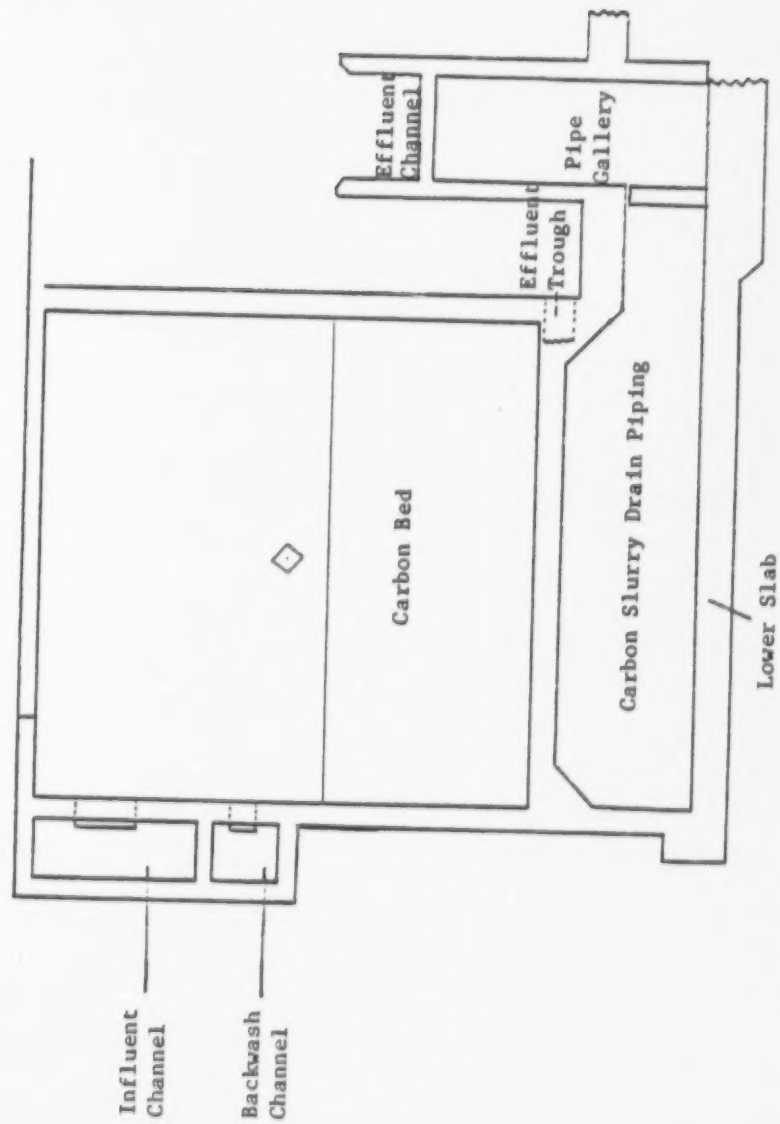


Figure 4-7. Section of concrete adsorber (complex design).

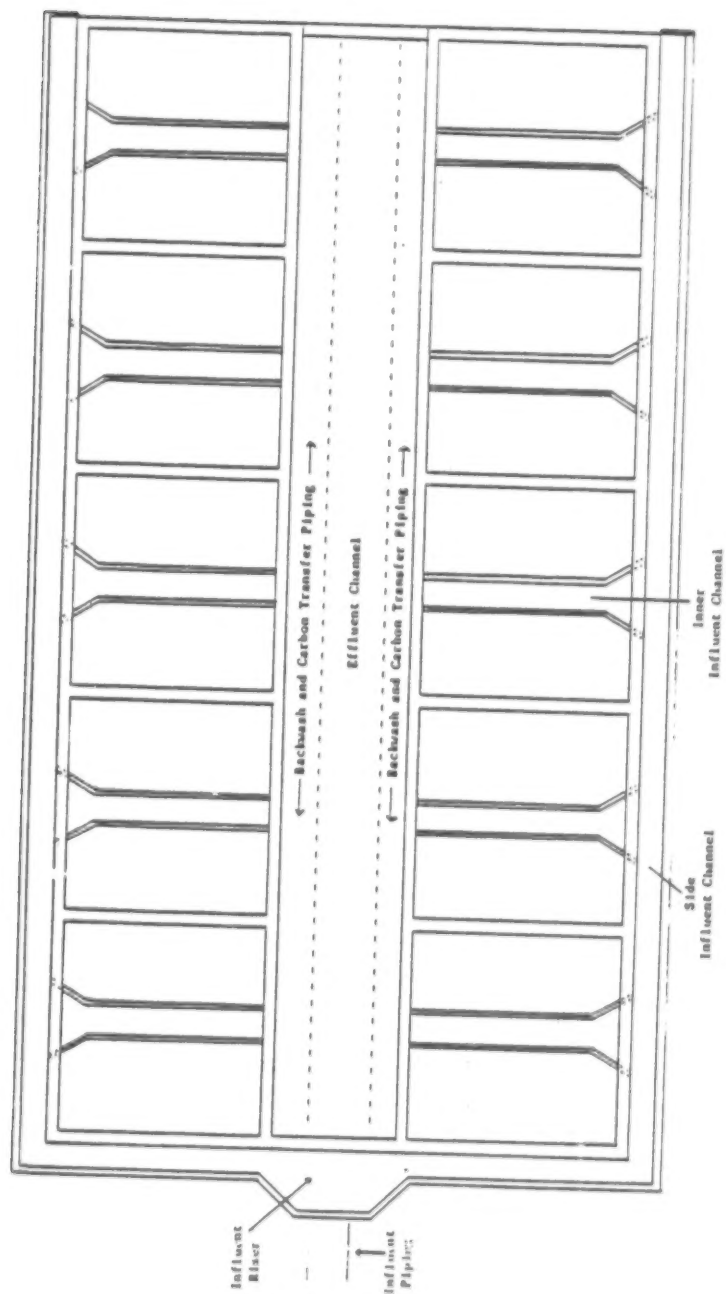


Figure 4-8. Plan of concrete adsorbers (complex case).

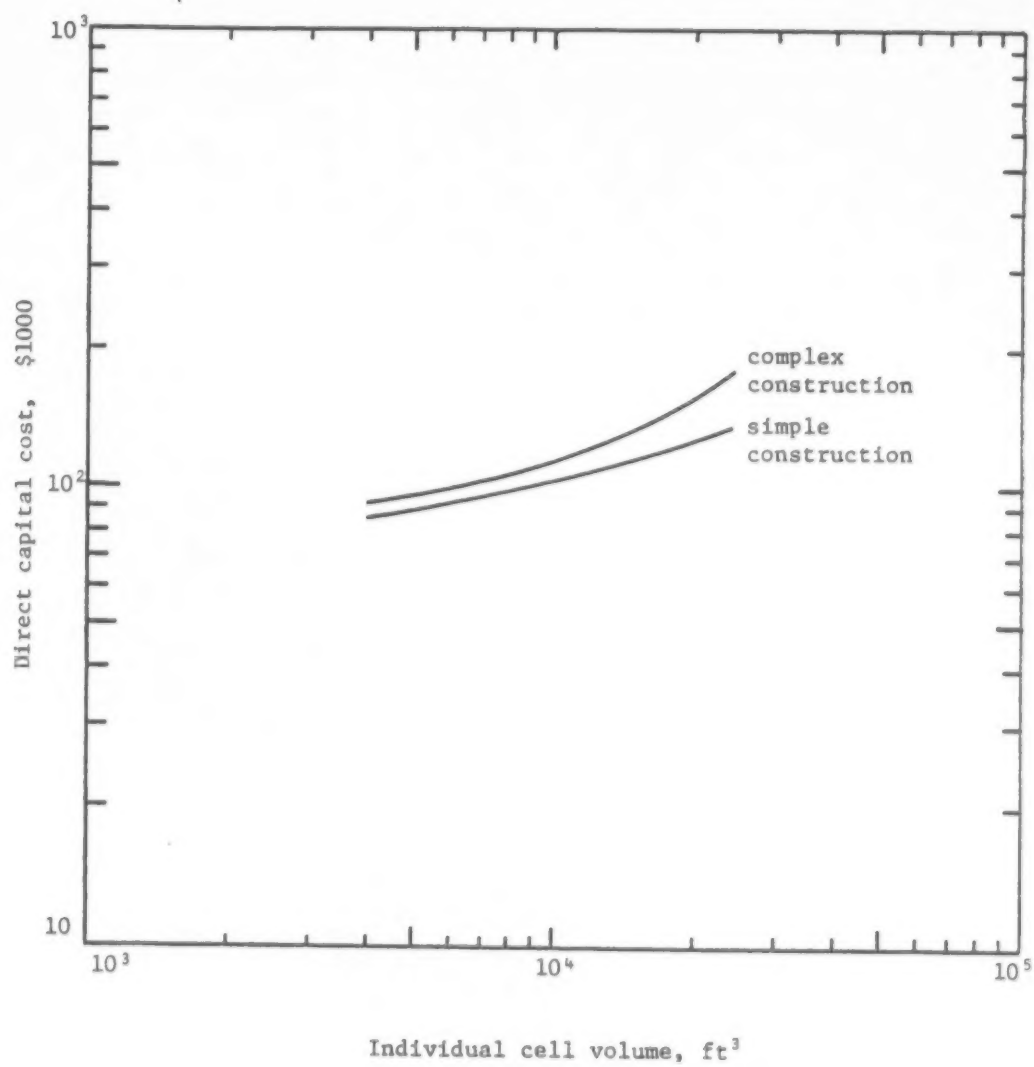


Figure 4-9. Concrete adsorber - direct capital cost.
(September, 1980 collars)

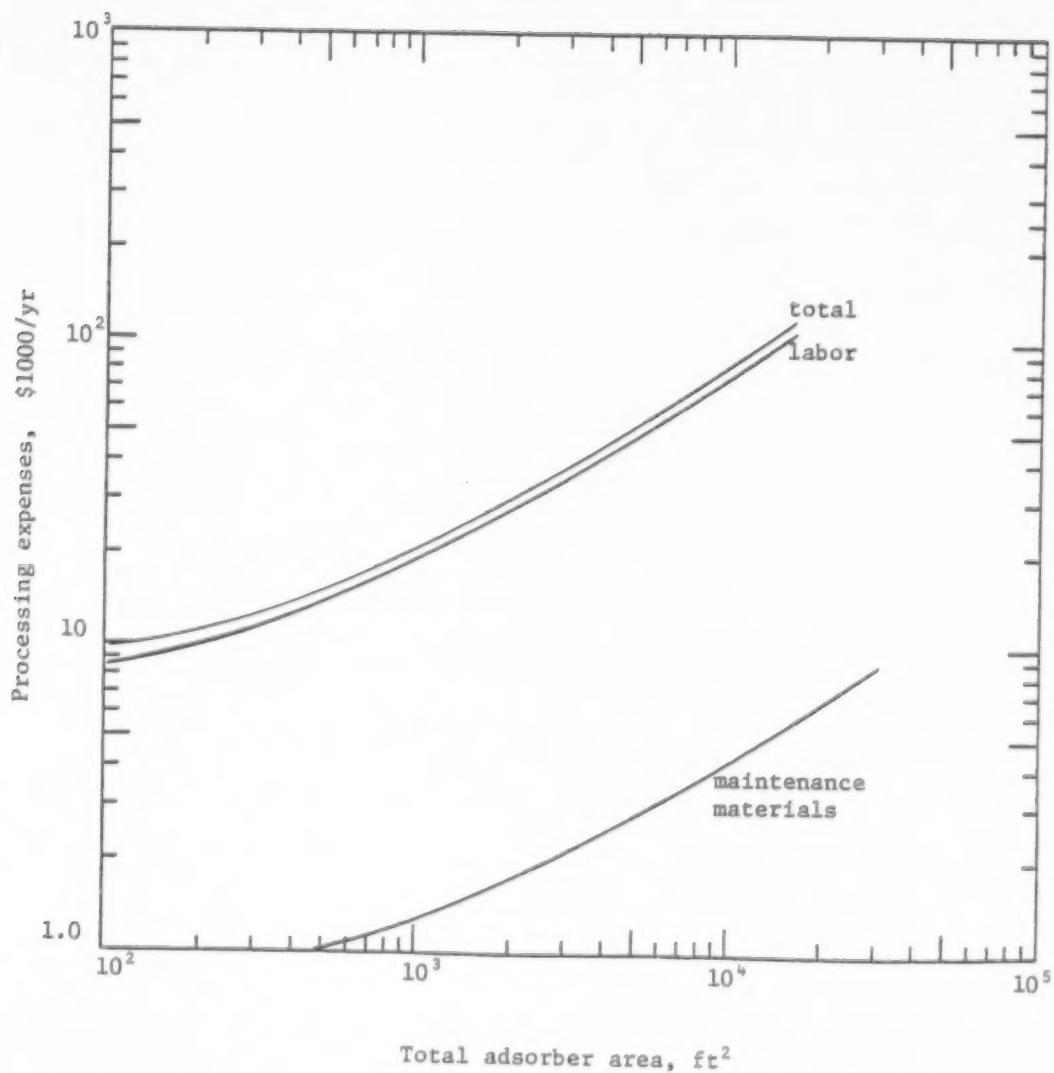


Figure 4-10. Concrete adsorber - processing expenses (September, 1980 dollars)

Cost References

Costs for the concrete structures were estimated using procedures in Reference 2 applied to drawings of actual concrete adsorbers. Costs for piping and valves were estimated from data in Reference 4 applied to conceptual designs for piping configurations for concrete adsorbers. Labor requirement estimates are from Reference 7.

Gravity Steel Adsorbers

Design Basis

Steel Vessels--The standard module consists of one vessel. A vessel is field fabricated with welded plate construction, and rests on a concrete slab foundation.

Vessels include bed support internals as well as influent and effluent liquid and carbon slurry distributors and collectors.

Piping Headers and Valves--Headers and valves for influent and effluent water, and inlet and outlet carbon slurry are included. Piping is constructed of Schedule 40 carbon steel, or 316 stainless steel pipe. For costing purposes valves are manual gate valves rated at 150 psig. Some valves in actual systems will be automatic.

Instrumentation--Instrumentation would include level sensors, flow meters, and automatic valving controls.

Direct Capital Cost

Direct capital cost is given in Figure 4-11 for 20 ft. and 30 ft. diameter adsorber systems.

Operating Requirements

Labor--Labor requirements are based on the total adsorber area.

Maintenance Materials--2 percent of direct capital cost.

Processing Expenses

Processing expenses are given in Figure 4-12.

Cost References

Vessel costs were derived from costs in Reference 7 by updating and by deletion of costs for housing, miscellaneous and contingency needs. Piping and valve costs were obtained from Reference 4 and applied to conceptual piping designs for the adsorbers. Labor requirement estimates are from Reference 7.

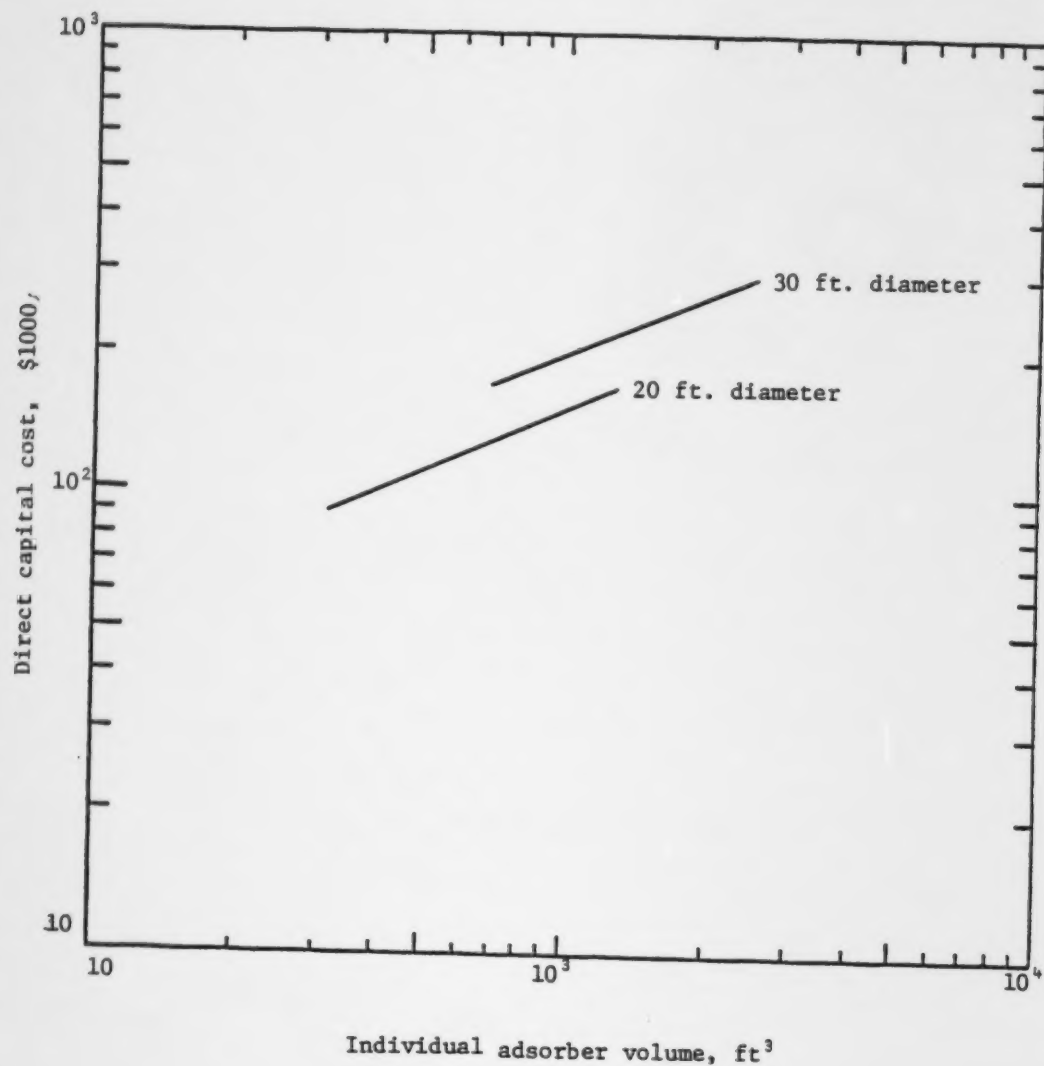


Figure 4-11. Gravity steel adsorbers - direct capital cost.
(September, 1980 dollars)

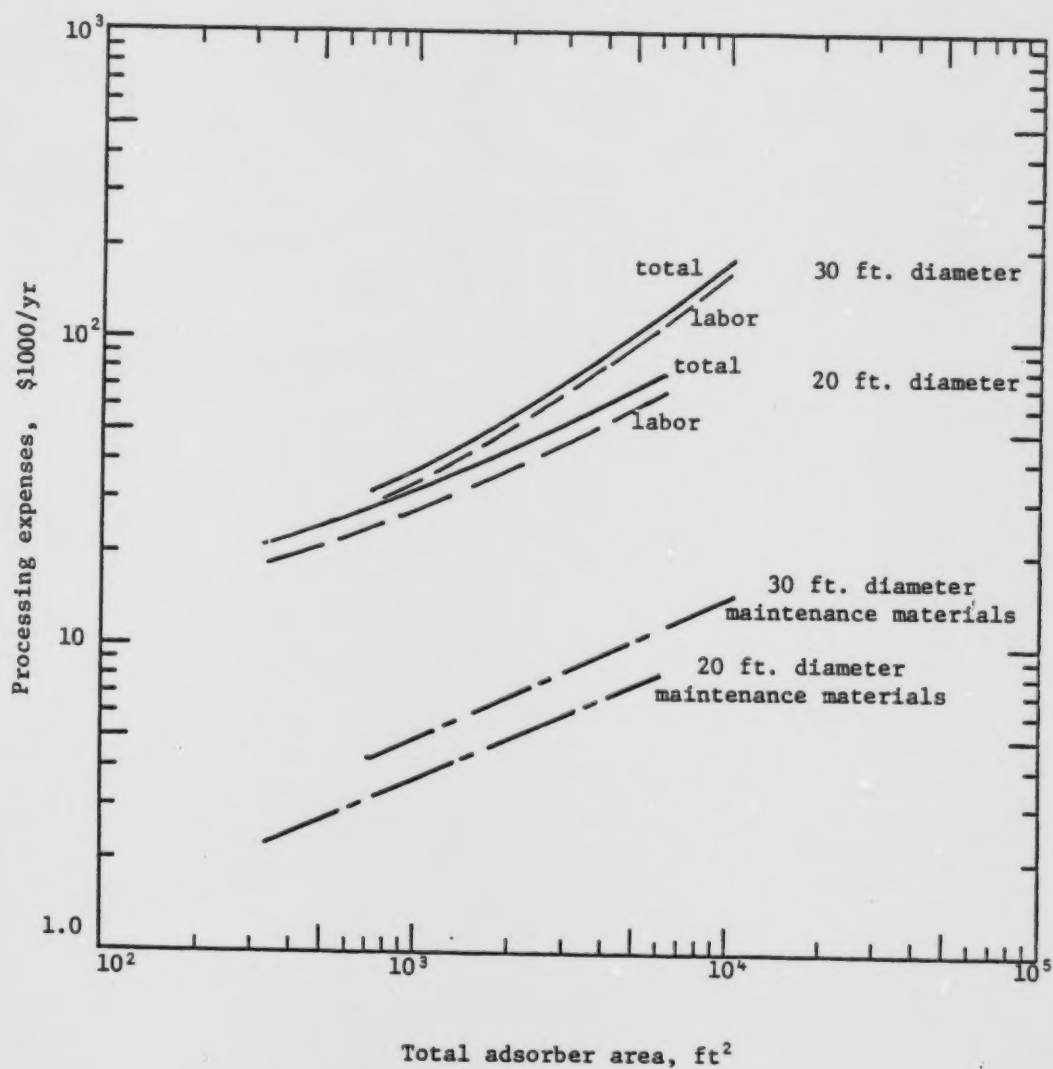


Figure 4-12. Gravity flow steel adsorber - processing expenses.
(September, 1980 dollars)

Pressure Steel Adsorbers

Design Basis

A typical pressure steel adsorber installation is illustrated in Figure 4-13.

Vessels—The standard module consists of a single cylindrical vertical vessel. Multiple vessels can be used as required to provide parallel or series flow configurations. The vessels are shop fabricated according to ASME code specifications for unfired pressure vessels. Seams are welded. The vessels can be lined for corrosion resistance with a variety of liner materials that include stainless steel cladding, rubber, and various polymeric coatings.

Vessels are supported on either angle steel, square tubular steel, or round tubular steel legs on concrete footings, on a concrete floor slab or directly on the ground. Tall vessels will require a steel support structure.

Standard ellipsoidal heads are used for these vessels in fixed bed upflow or downflow service.

Vessels include bed support internals as well as influent and effluent liquid and carbon slurry distributors and collectors.

Piping Headers and Valves—Headers and valves for influent and effluent water, and inlet and outlet carbon slurry are included. These are constructed of Schedule 40 carbon steel, or 316 stainless steel pipe. Valves for costing purposes are manual gate valves. In actual systems some automatic valves will be used.

Instrumentation—Instrumentation would include level sensors, flow meters, and automatic valving controls.

Direct Capital Cost

Direct capital costs are given in Figure 4-14.

Operating Requirements

Labor—Labor requirements are based on total adsorber area.

Maintenance Materials—2 percent of direct capital cost.

Processing Expenses

Processing expenses are given in Figure 4-15.

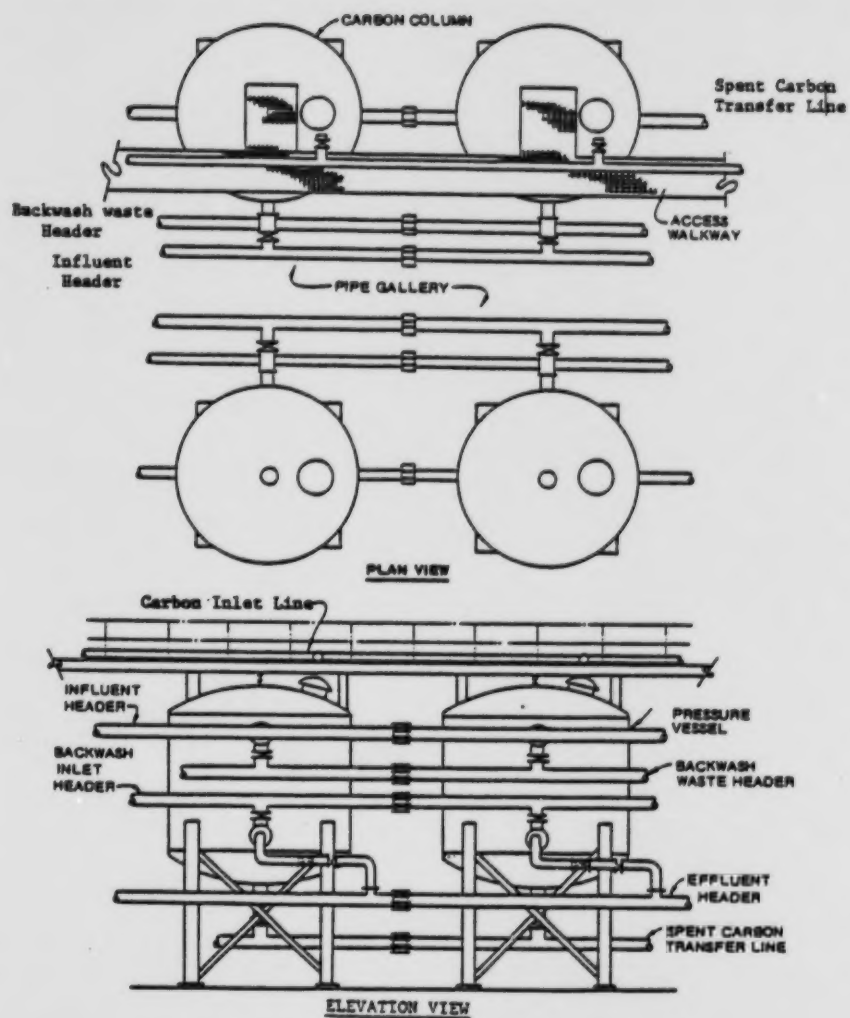


Figure 4-13. Typical fixed bed downflow pressure vessel granular activated carbon installation.

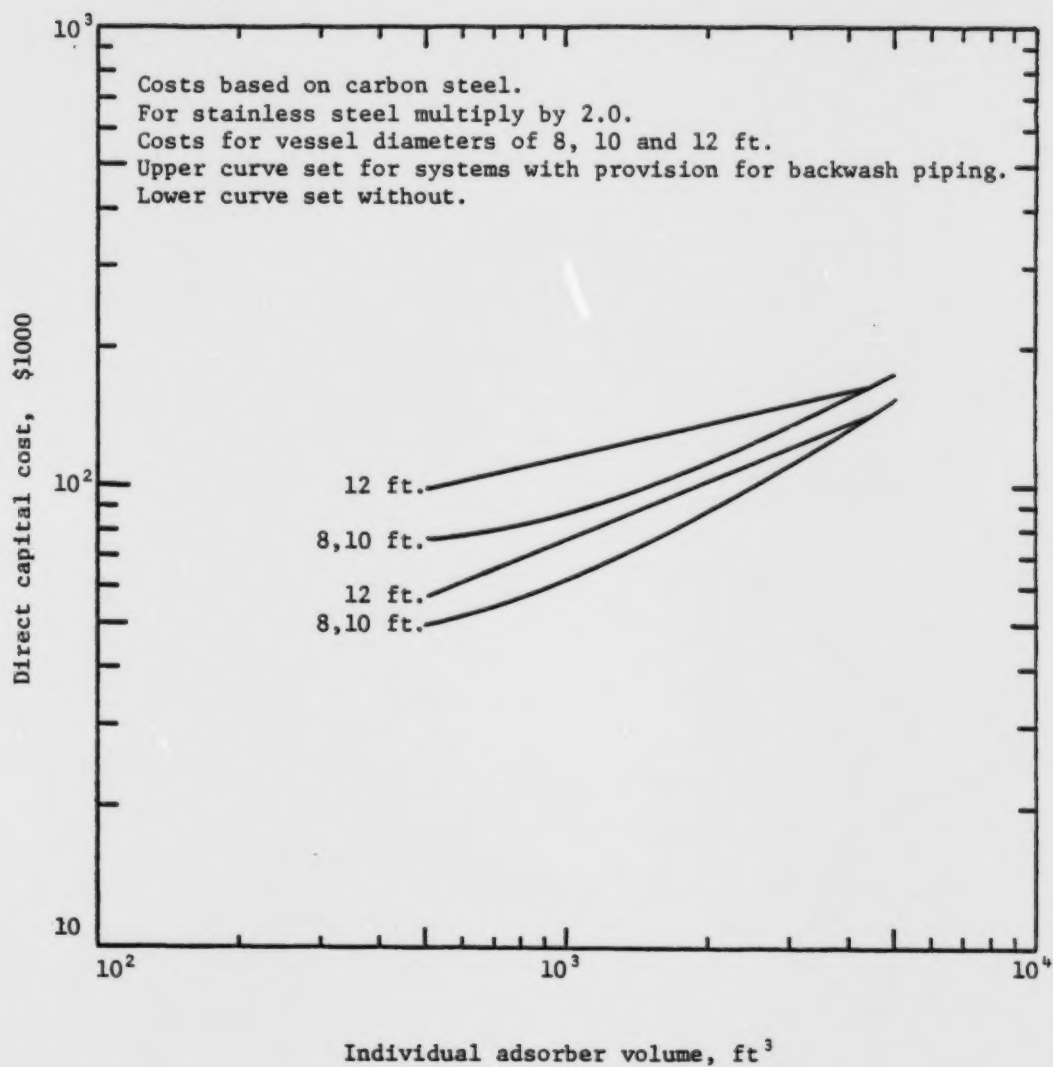


Figure 4-14. Pressure flow steel adsorbers - direct capital cost.
(September, 1980 dollars)

Cost References

Adsorber costs were developed using procedures for steel pressure vessels in Reference 2. Piping and valve costs are based on costs in Reference 4 applied to conceptual designs of piping configurations for pressure steel adsorbers. Labor requirement estimates are from Reference 7.

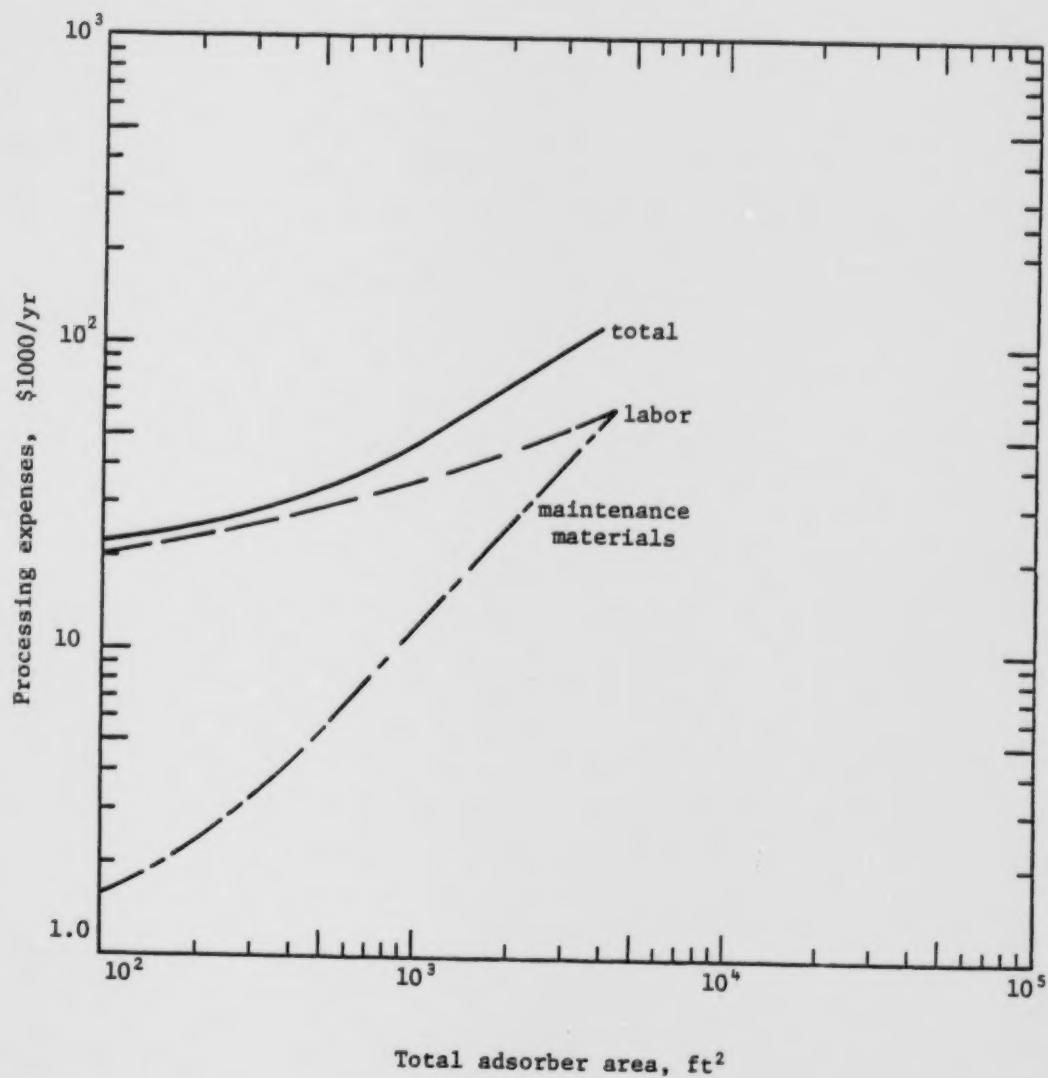


Figure 4-15. Pressure flow steel adsorber - processing expenses.
(September, 1980 dollars)

Pulsed-bed Steel Adsorbers

Design Basis

A conceptual design of one type a pulsed-bed adsorber is shown in Figure 4-16. Other types resemble the fixed-bed absorbers shown previously.

Vessel--The standard vessel is cylindrical steel with a conical bottom. The vessels can be lined for corrosion resistance with a variety of materials which include stainless steel cladding, rubber, and various polymeric coatings.

The vessel is supported with legs of angle steel, square or tubular steel resting on concrete footings which, in turn, rest on a concrete floor slab or directly on the ground. Tall vessels will require a steel support structure.

Peripherals--Additional equipment associated directly with the vessel include the carbon feeder chamber and various on-vessel piping and fittings. Rotary valves for pulse discharge of carbon slurry are located at bottoms of feed hoppers and main vessel. Piping is Schedule 40 carbon steel or 316 stainless steel. Valves for costing purposes are manual gate valves. Cost differences between these and rotary and automatic valves will be accounted for in the contingency allowance applied to total system costs.

Direct Capital Cost

Direct capital costs are given in Figure 4-17. These costs are applicable to the adsorber type shown in Figure 4-16. For other types use costs for fixed bed adsorbers without backwash.

Operating Requirements

Labor--Labor requirements are based on total adsorber area and are assumed to be the same as for fixed bed pressure steel adsorbers.

Maintenance Materials--2 percent of direct capital cost.

Processing Expenses

Processing expenses are given in Figure 4-18. The same comments apply as with direct capital cost.

Cost References

Adsorber costs were developed using the procedures for steel pressure vessels in Reference 2 applied to a conceptual pulsed-bed adsorber design. Piping and valve costs are based on costs in Reference 4 applied to a conceptual design of a piping configuration for pulsed-bed adsorbers. Labor requirements were assumed to be the same as for pressure steel vessels and were obtained from Reference 7.

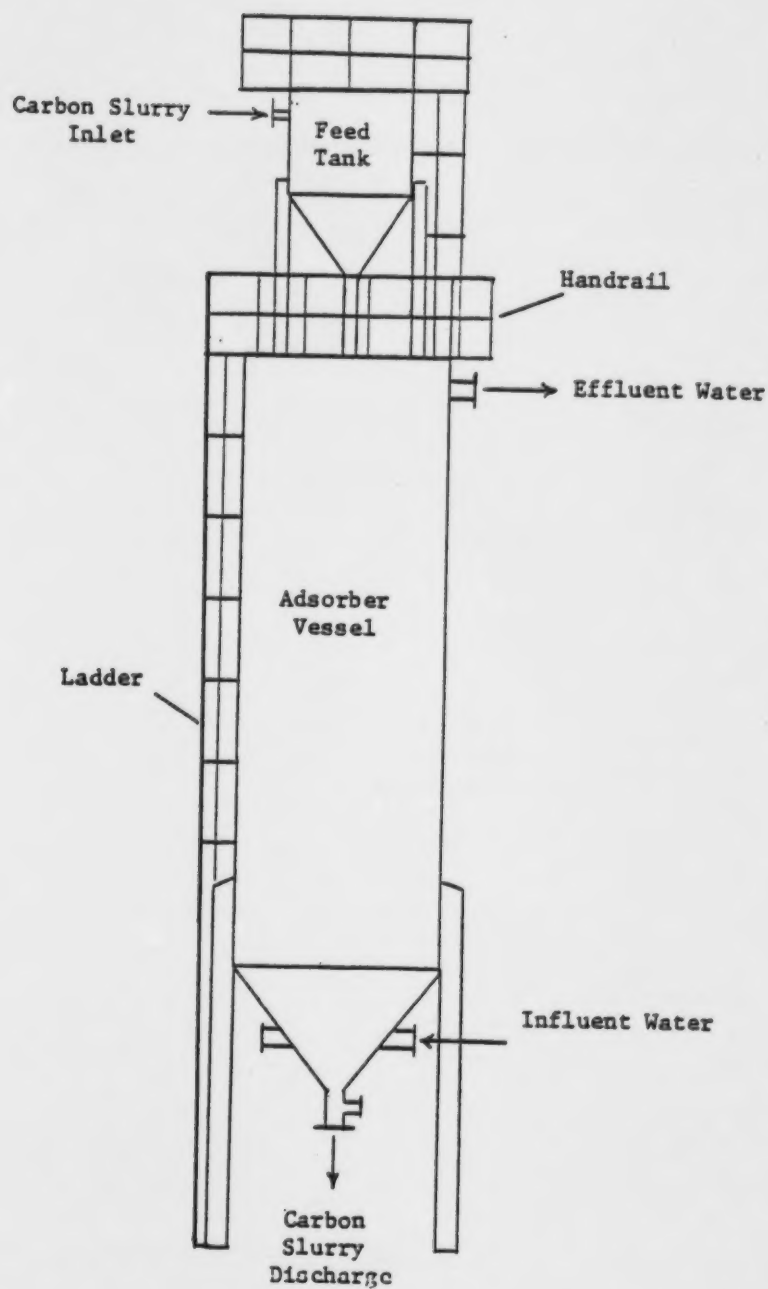


Figure 4-16. Pulsed-bed adsorber with top mounted carbon feed tank.

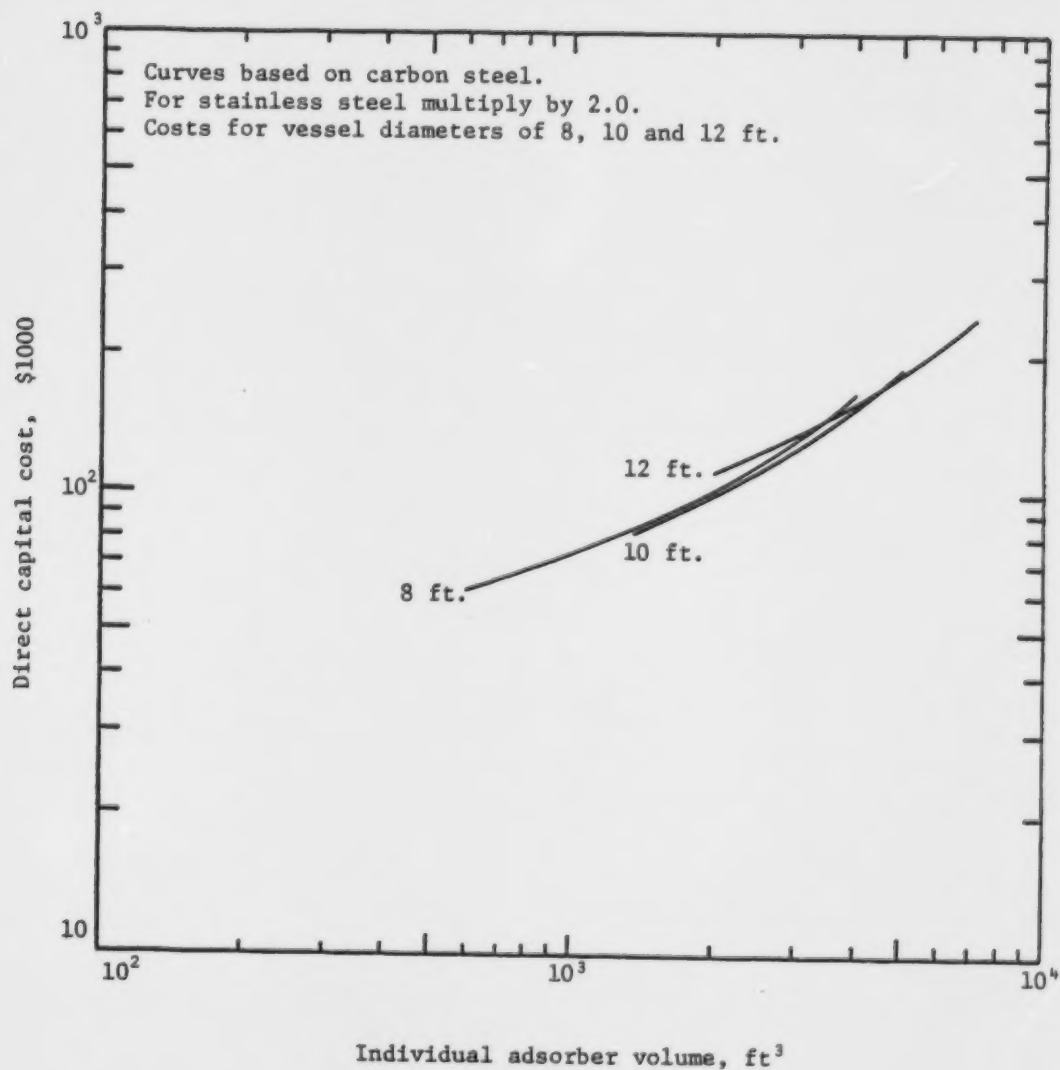


Figure 4-17. Pulsed bed adsorber - direct capital cost.
(September, 1980 dollars)

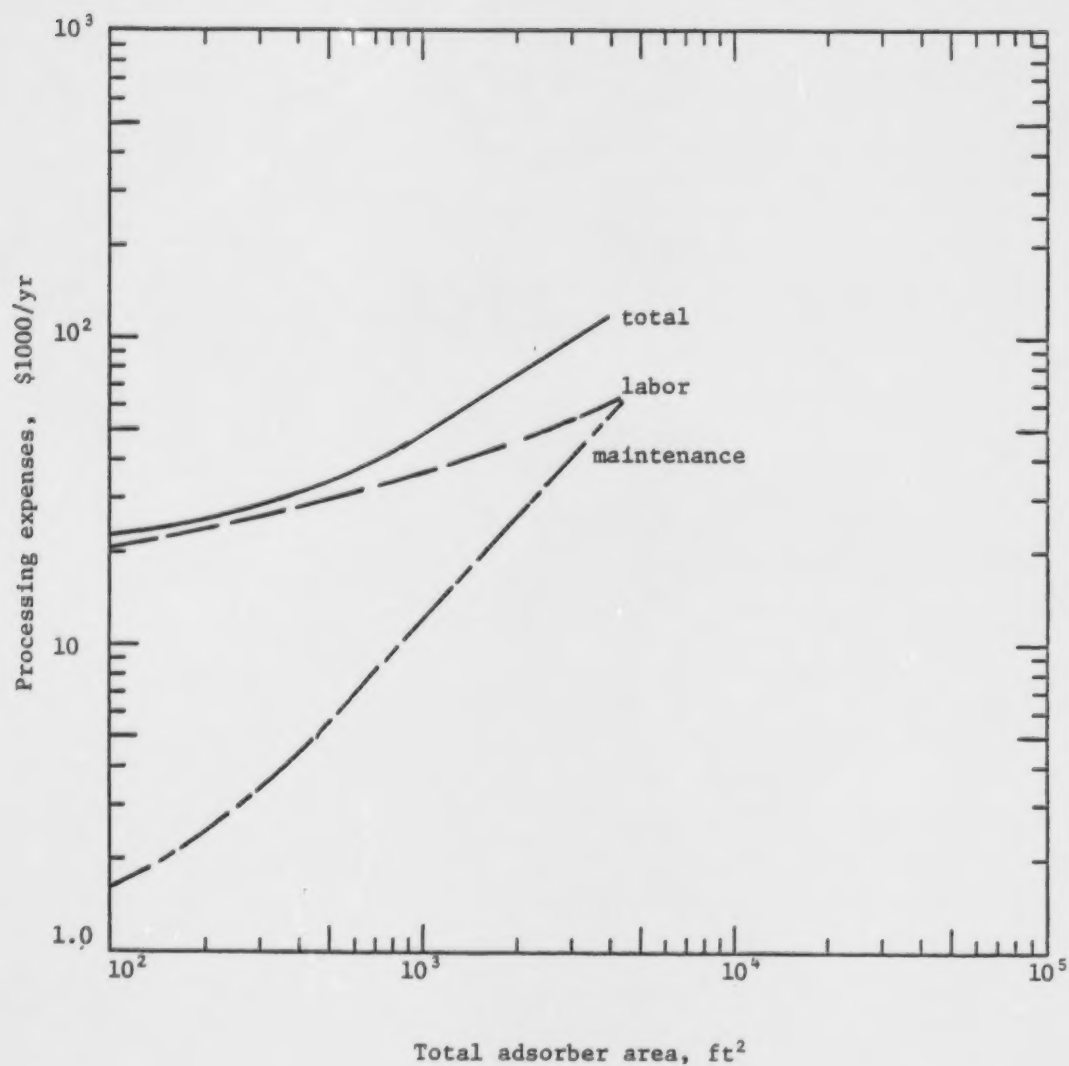


Figure 4-18. Pulsed bed adsorber - processing expenses (September, 1980 dollars)

Packaged Adsorber Systems

Packaged, pre-assembled, skid-mounted adsorber systems are commercially available from a number of vendors. These systems can vary in the specific equipment items included in the assembly. Costs here were adjusted and updated from literature-reported costs on packaged systems.

Design Basis

The packaged assembly is skid-mounted and uses a single pressure steel adsorber vessel of carbon steel rated for 50 psig. Included are piping, valves, controls, and supply and backwash pumps. Upon installation, the unit requires only connections to influent and effluent piping, electrical, and instrument air lines.

Direct Capital Cost

Direct capital costs are presented in Figure 4-19. The cost of the initial carbon change must be added separately.

Operating Requirements

Labor requirements are based on essentially unattended operation. Labor is required for backwashing (weekly), routine maintenance and performance monitoring. Maintenance materials include routine items such as pump seals and lubricants. Electricity is required for supply and backwash pumping.

Processing Expenses

Processing expenses are presented in Figure 4-20. Makeup granular activated carbon costs are not included.

Cost References

Costs were adjusted and updated from Reference 7.

4.2.2 Backwash Equipment

Backwashing is an option for adsorbers. Costs for backwashing are therefore presented separately from costs for the adsorbers themselves. A backwash module comprises either pumps alone, or pumps in combination with a storage vessel for backwash wastewater. Clean water for the backwash system is drawn from the system effluent which is assumed to be held in storage vessels. Costs for these vessels are not included as part of the backwash system. Backwash wastewater is disposed of by pumping it back to either the upstream end of the overall treatment system of which GAC is a part, or to a sewer system. Costs for such disposal outside the battery limits of the GAC system are not included.

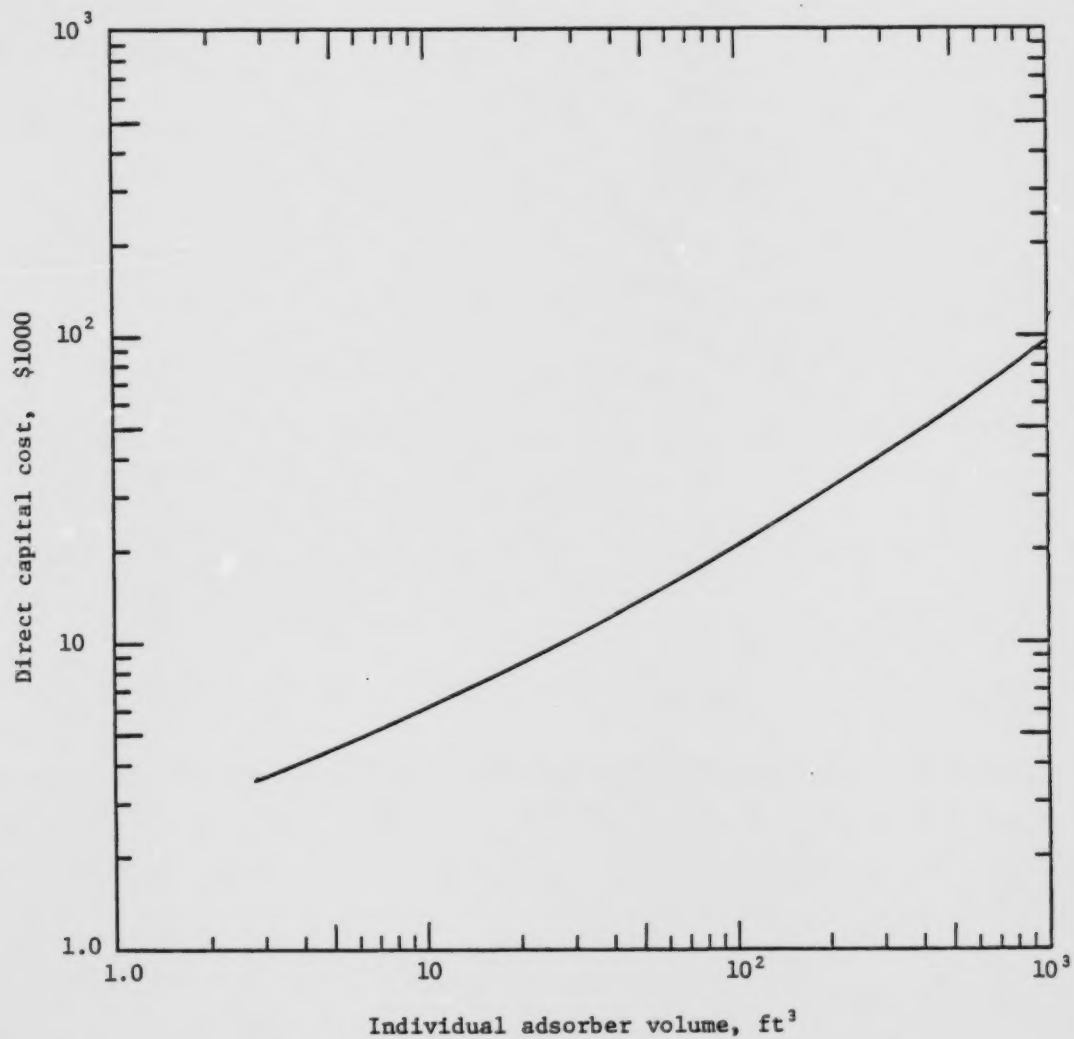


Figure 4-19. Packaged adsorber system - direct capital cost
(September, 1980 dollars)

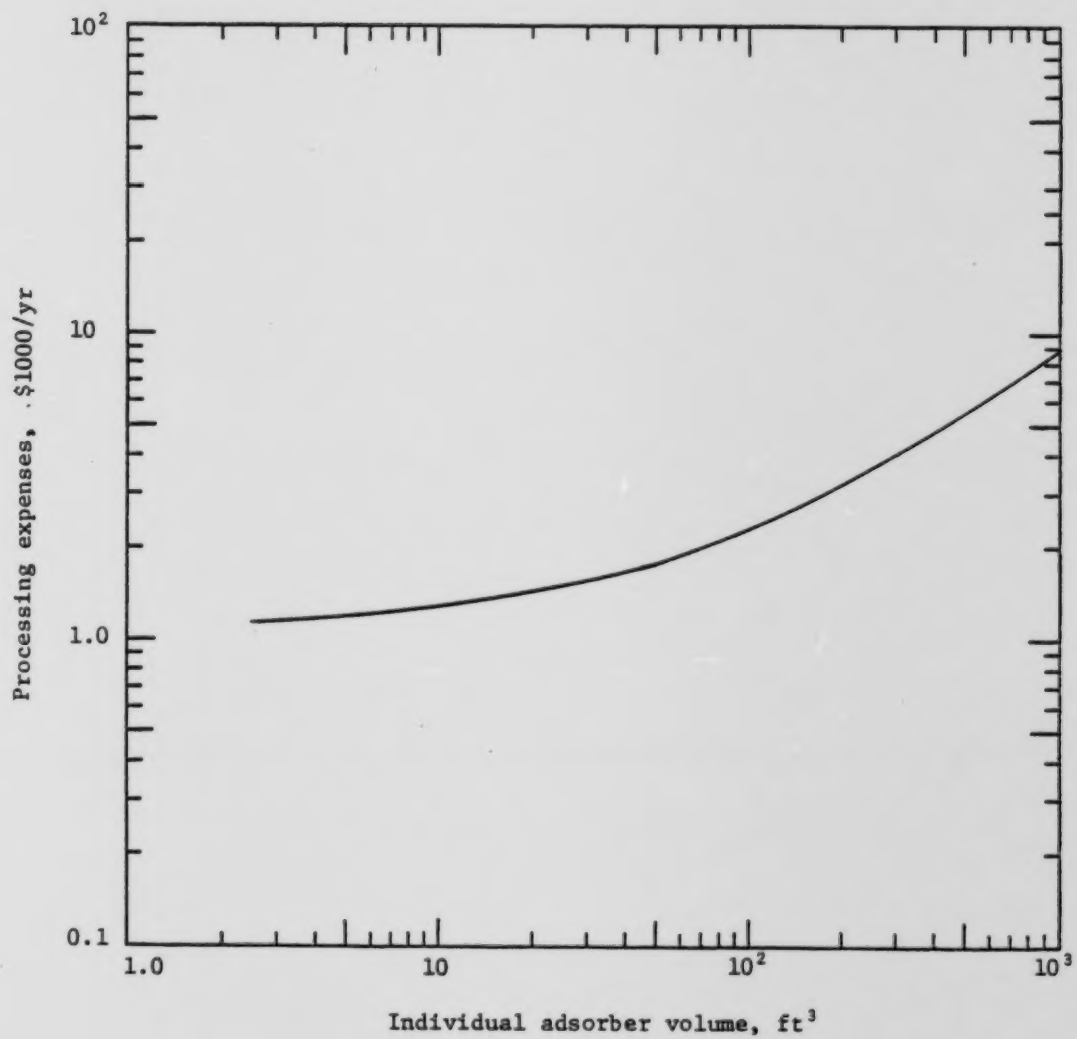


Figure 4-20. Packaged adsorber systems - processing expenses (September, 1980 dollars)

Design Basis

A conceptual design of a backwash system is illustrated in Figure 4-21.

Backwash Wastewater Vessel--A backwash wastewater vessel is provided as surge capacity until the wastewater can be transferred back to a treatment step upstream from the GAC unit. The tank includes a transfer pump for final disposition of the backwash effluent.

Backwash Pumps--Two electrically-powered centrifugal pumps are provided for backwashing, one for operation and one as a spare.

Instrumentation--Instrumentation would include flow control, flow metering, backwash sequence controls.

Direct Capital Cost

Direct capital costs are given in Figure 4-22.

Operating Requirements

Labor--Labor requirements are based on the total adsorber area.

Maintenance Materials--2 percent of direct capital cost.

Power--0.3 kW per ft³ of adsorber area for a backwash rate of 18 gpm/ft³, and a 50 ft pumping head.

Processing Expenses

Processing expenses are given in Figure 4-23.

Cost References

Storage vessel costs were developed from Reference 2. These costs include piping. Pump costs are from Reference 4. Labor requirements were estimated from Reference 7.

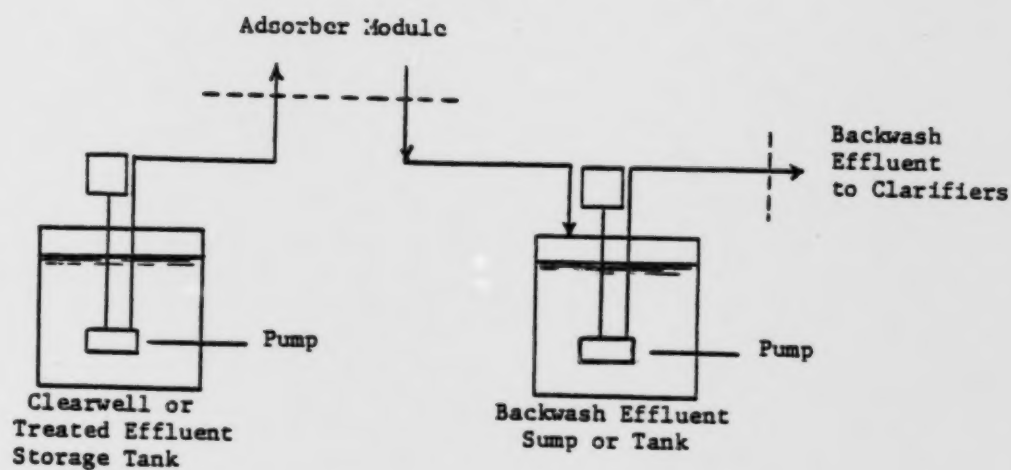


Figure 4-21. Backwash module.^a

^a Submersible pumps shown for illustrative purposes only. At grade tanks would use in-line centrifugal pumps and below grade concrete vessels and sumps would use submersible pumps.

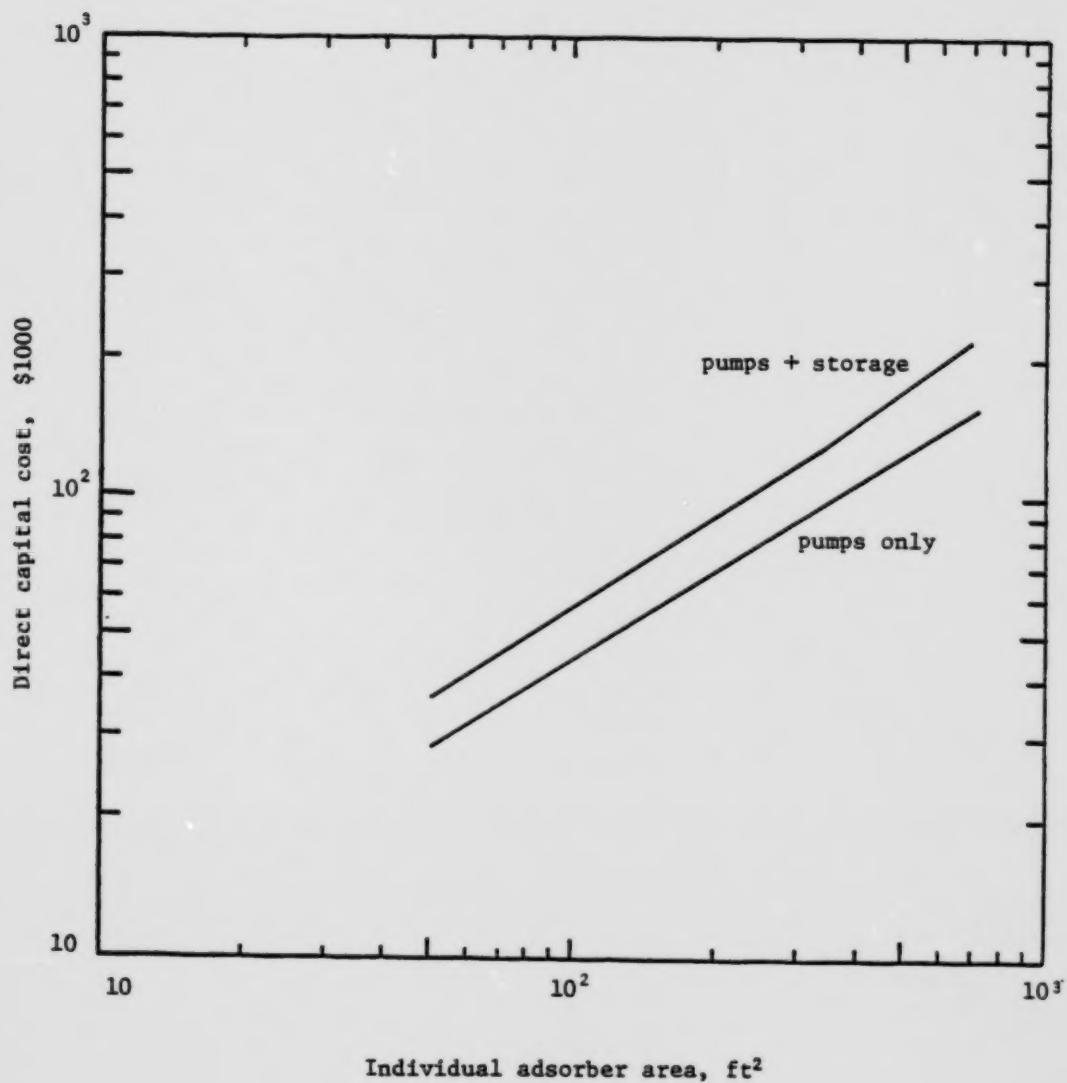


Figure 4-22. Backwash module - direct capital cost.
(September, 1980 dollars)

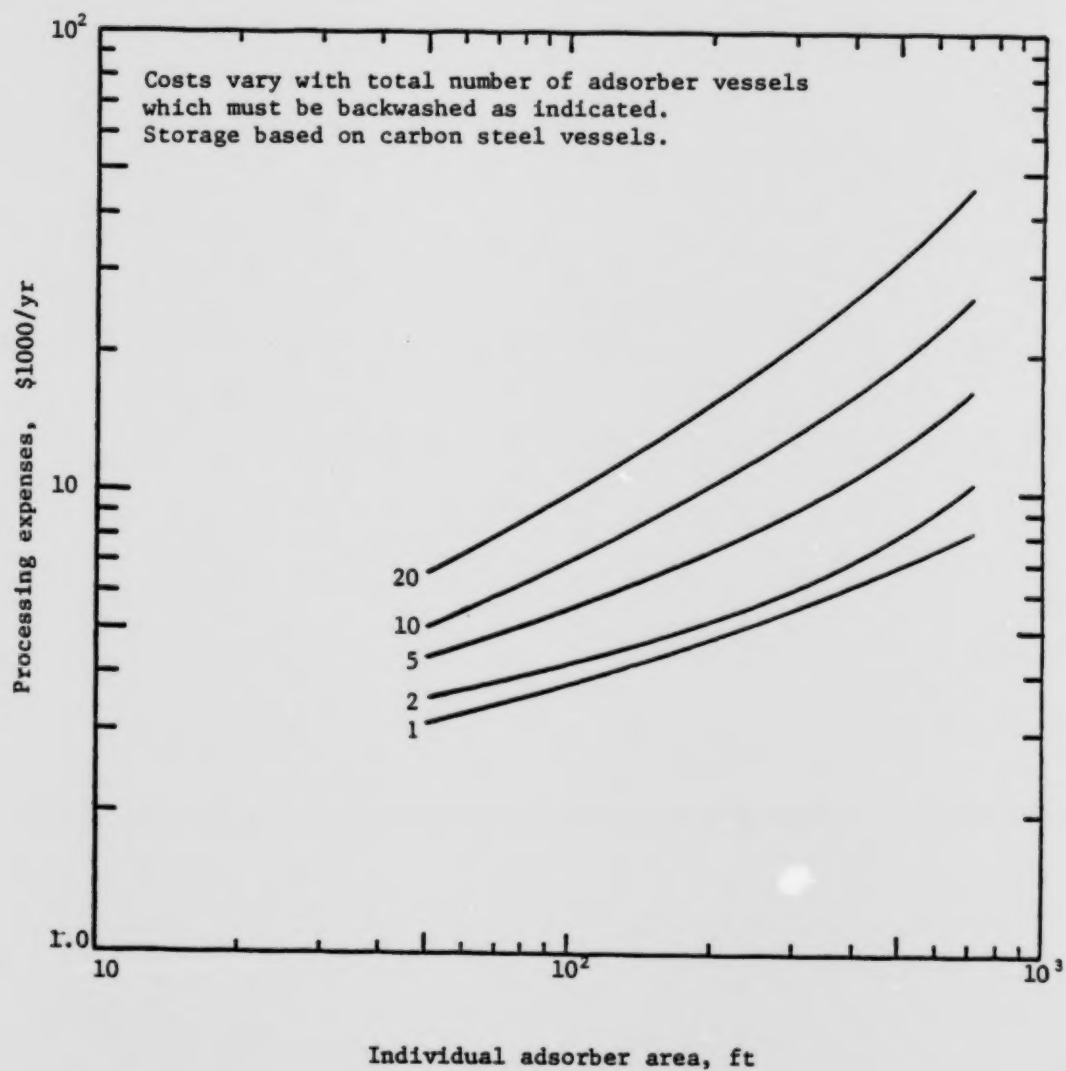


Figure 4-23. Backwash module - processing expenses.
(September, 1980 dollars)

4.2.3 Surface Wash Equipment

Like the backwash system, the surface wash system is optional. It will be used on certain downflow adsorbers in applications where solids compacted at the bed surface might require removal to maintain bed flow rate at a specified head. The surface wash module includes the pumps and the piping assembly within the adsorbers themselves. It has been assumed that surface wash will only be used when backwash is used. The water supply for surface wash will be the same as for backwash and surface wash wastewater will be disposed of with backwash wastewater.

Design Basis

An illustration of two surface wash piping arrangement within adsorbers is shown in Figure 4-24.

Surface Wash Pumps—Two electrically-powered centrifugal pumps with motors, one operating and one as standby, piping and valves directly associated with the pumps, and electrical controls.

Instrumentation—Instrumentation would include flow metering, surface wash sequence controls, and flow control.

Direct Capital Cost

Direct capital costs are given in Figure 4-25.

Operating Requirements

Labor—Labor requirements are based on the total adsorber area.

Maintenance materials—2 percent of direct capital cost.

Power—0.097 kW per ft² of adsorber area based on a surface wash rate of 1.5 gpm/ft², and a 200 ft pumping head.

Processing Expenses

Processing expenses are given in Figure 4-26.

Cost References

Pump costs were developed from costs in Reference 4. Piping costs for the surface wash structure in the adsorber were based on costs from Reference 4 applied to conceptual designs for surface wash structures.

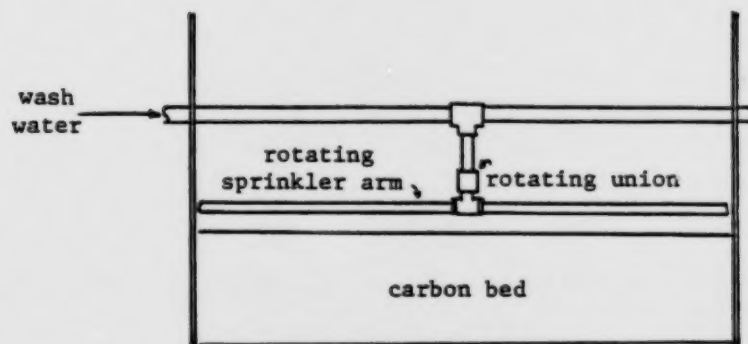
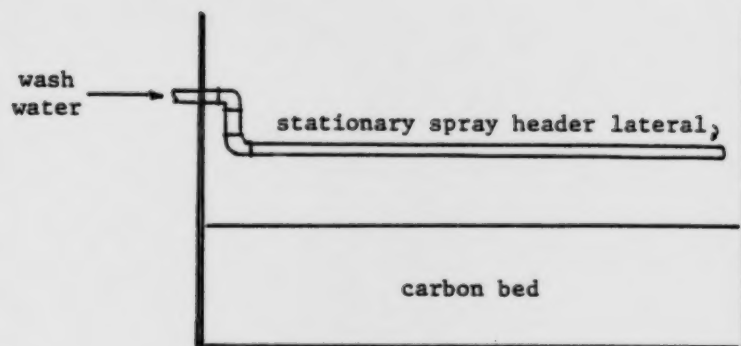


Figure 4-24. Two types of surface wash assemblies within adsorbers.

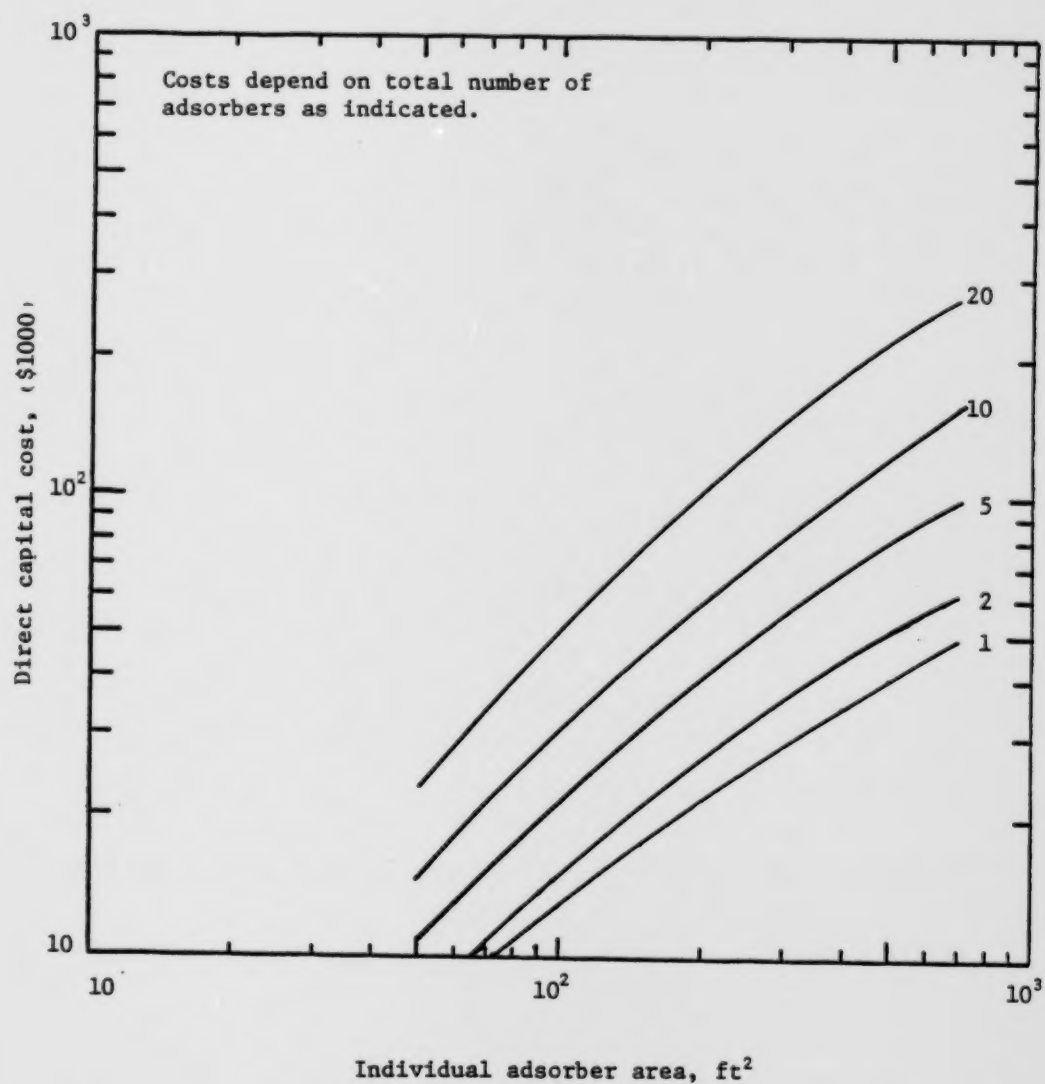


Figure 4-25. Surface wash module - direct capital cost.
(September, 1980 dollars)

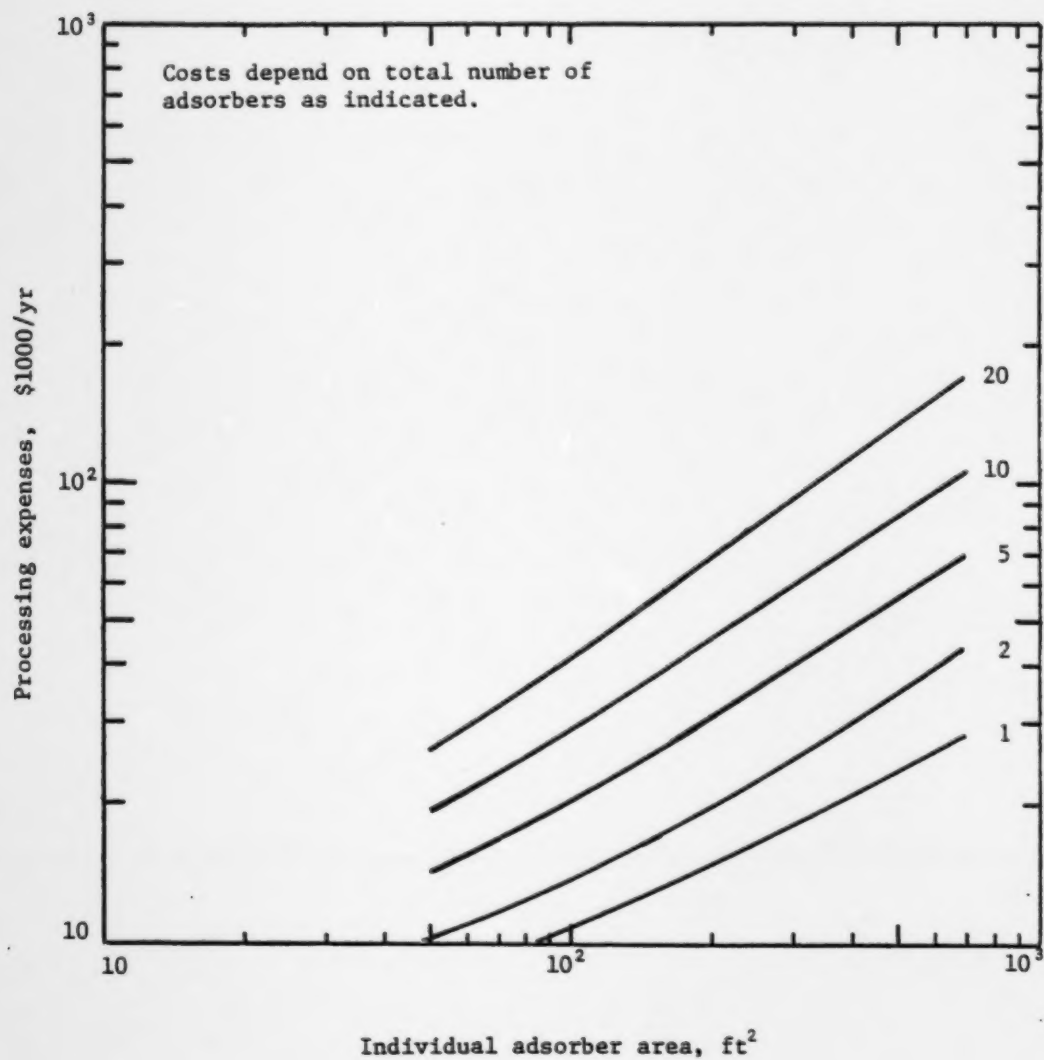


Figure 4-26. Surface wash module - processing expenses (September, 1980 dollars)

4.2.4 Air Scour System

Air scouring can be used in conjunction with backwashing to loosen solids deposited within the carbon bed. Costs of air scouring depend on the air rate required, frequency and duration of scouring, and the depth of the carbon bed and vessel.

An air compressor supplies air through piping to a distribution header within an adsorber vessel.

Design Basis

Costs are based on the use of a centrifugal air compressor. The superficial air rate to the adsorber during scouring is 7.5 scfm/ft² of individual adsorber area. The compressor includes an electric motor with gear drive. The overall efficiency of the compressor system was assumed to be 70 percent.

Direct Capital Cost

Direct capital cost is given in Figure 4-27.

Operating Requirements

The primary operating requirements are for electricity and maintenance. Electricity requirements were computed based on a 70 percent overall compressor system efficiency. Major maintenance materials include lubricants and compressor seals. The cost of these materials is assumed to amount to 2.5 percent of the direct capital costs, with maintenance labor costs equivalent to the cost of maintenance materials.

Processing Expenses

The processing expenses are given in Figure 4-28. Only a total curve is provided.

Cost References

Compressor costs were updated from Reference 4.

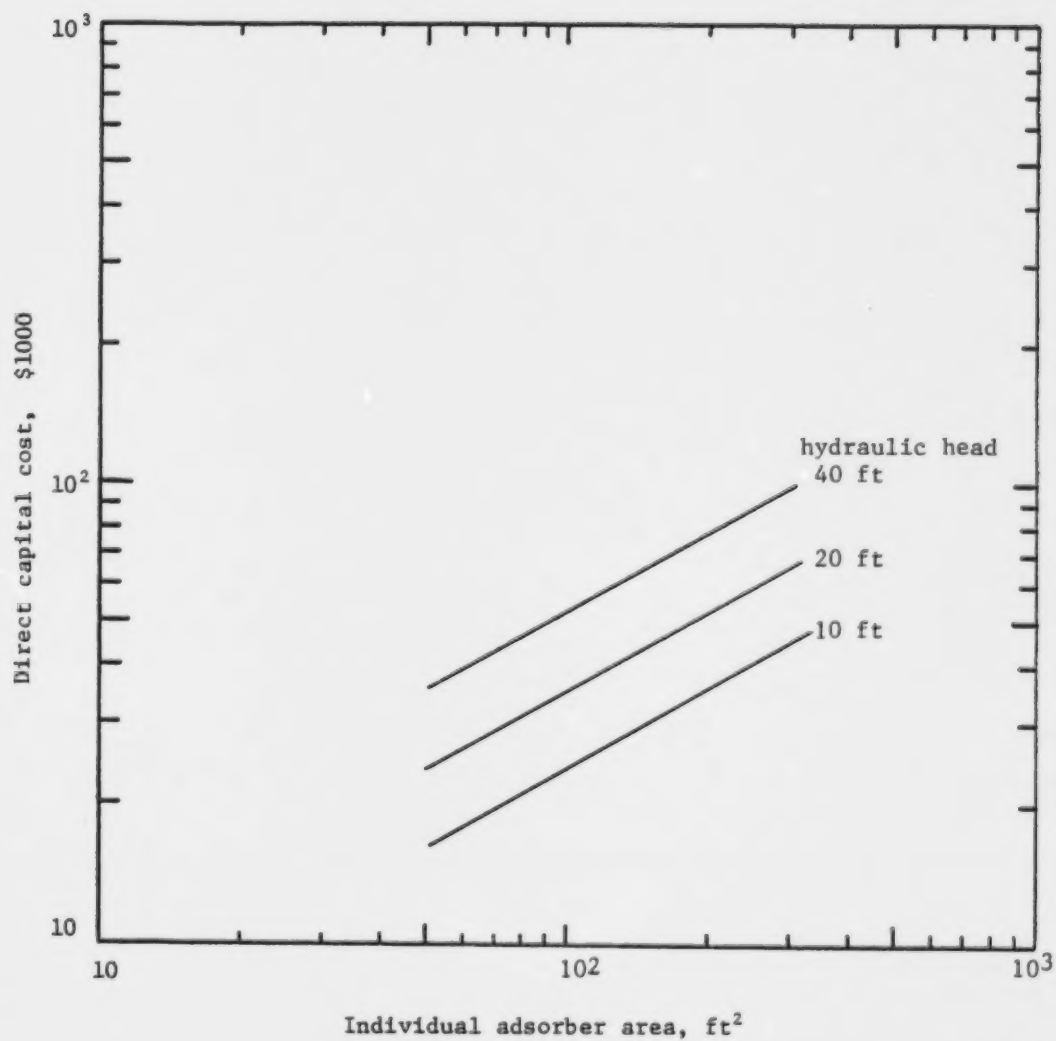


Figure 4-27. Air scour system - direct capital cost
(September, 1980 dollars)

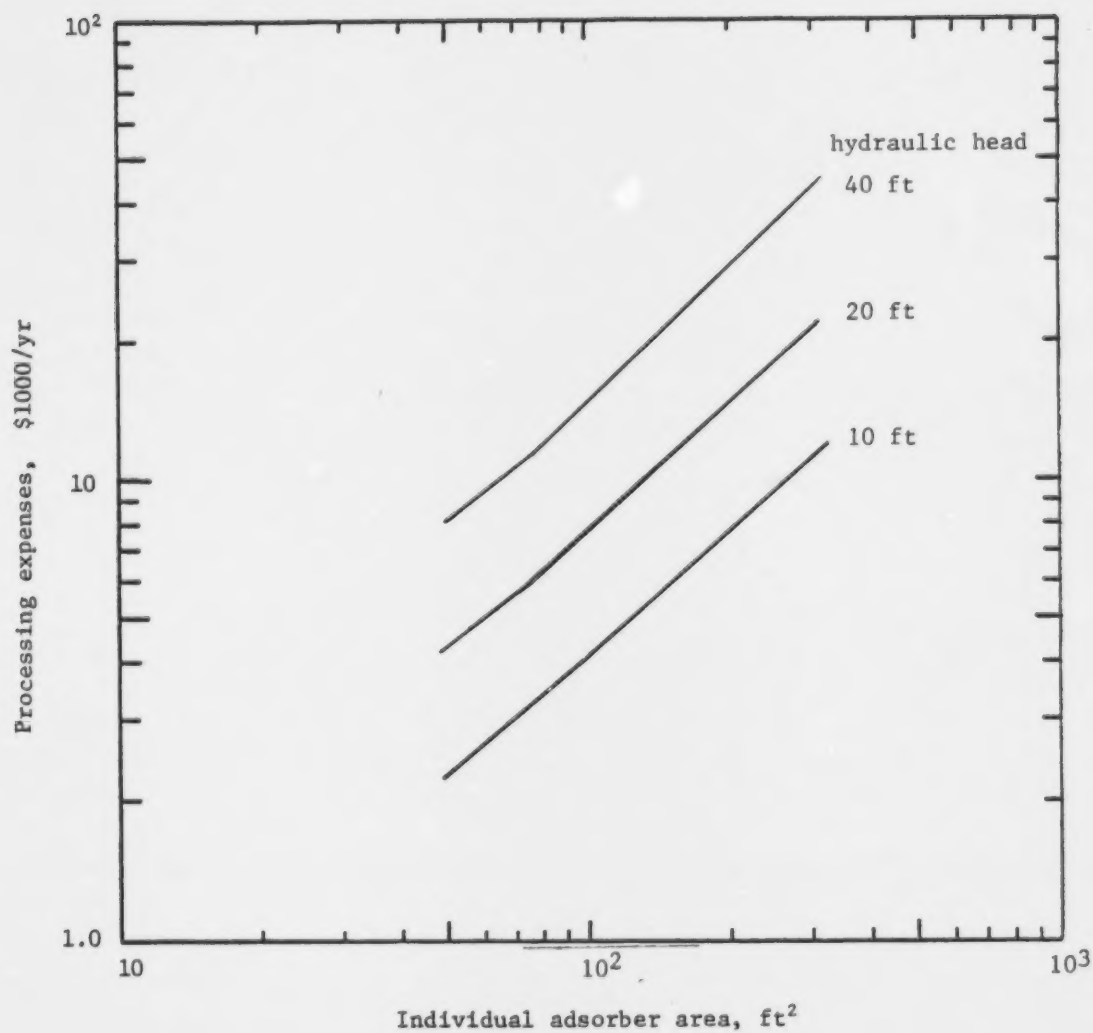


Figure 4-28. Air scour system - processing expenses
(September, 1980 dollars)

4.2.5 Initial Carbon Charge

The cost of the initial carbon charge in a new facility is treated as a capital cost. The initial carbon charge was therefore defined as a process module. Costs for the initial carbon charge apply only to carbon in the adsorbers. No carbon stored outside the adsorbers themselves is included.

Specifications and Direct Capital Cost

Several types of granular activated carbon are commercially available. They differ in cost by type, particle size, vendor, and time. The capital cost for the initial carbon charge depends on the total weight of carbon and its price. Carbon volume is calculated by determining the percentage of adsorber volume actually filled with carbon and multiplying that by the bulk density of the carbon to obtain the weight of carbon.

Direct capital costs shown in Figure 4-29 are based on a price of \$0.75/lb and a bulk density of 30 lb/ft³ for both 8 x 30 mesh and 12 x 40 mesh granular activated carbon.

Cost References

Because carbon price fluctuates and is subject to contract negotiation, only an average or typical price could be used here. Carbon prices will vary with the grade, manufacturer, and time and terms of purchase. The cost of \$0.75/lb is based on a value reported in Reference 12.

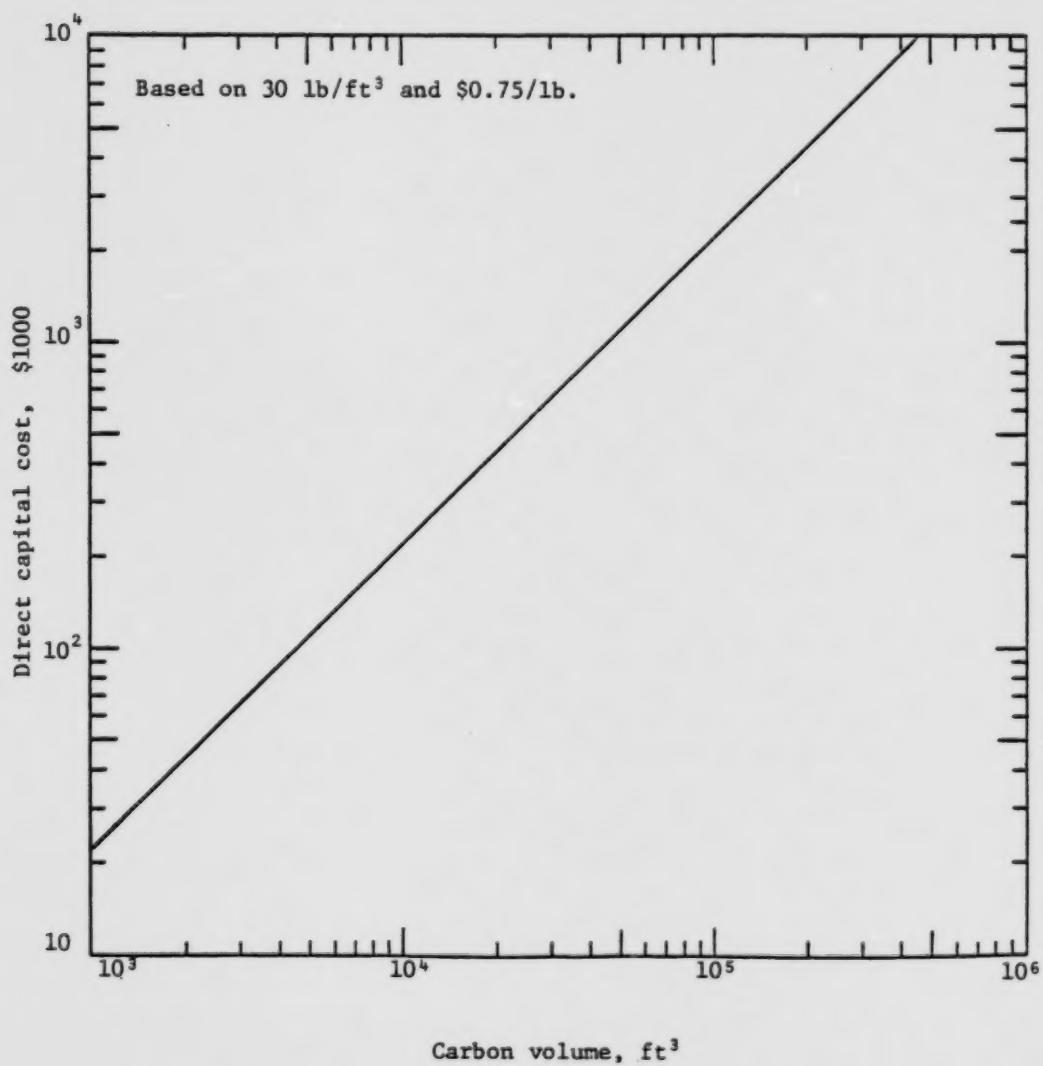


Figure 4-29. Initial carbon charge - direct capital cost.
(September, 1980 dollars)

4.3 REGENERATION SUBSYSTEM

Four kinds of regeneration systems considered as process modules are:

- multihearth furnaces,
- fluid-bed furnaces,
- infrared furnaces, and
- off-site regeneration.

Among the first three systems, multihearth furnaces have the most operating experience, while fluidized beds and infrared ovens applied to granular activated carbon regeneration have only recently been applied commercially.

Off-site regeneration might employ any of these three methods of regeneration. Off-site regeneration is usually provided as a service by an outside contractor. Costs for off-site regeneration can be lower than for on-site regenerations depending on the quantity of carbon involved, regeneration frequency, distance to the regeneration facility, and the share of the total facility costs allocated to the specific user.

4.3.1 Multihearth Regeneration Furnaces

Design Basis

Basic Furnace—An overall multihearth installation was shown in Figure 3-7. The basic multihearth furnace consists of a cylindrical steel shell divided vertically into compartments or "hearths." The shell is lined with refractory material. Standard furnaces range in size from 36 inches to 25 feet in diameter and 9 feet to 49 feet in overall height depending on carbon throughput rate, hearth loading of the carbon, and the number of hearths (11). The number of hearths can range from 4 to 12. Hearth areas represented in the cost curves range from 27 to 1509ft². A hearth loading of 40 lb/ft²-day was the basis for design and estimating the electricity and natural gas requirements. A moisture level in the inlet carbon of 50 percent was the basis for determining energy requirements.

Furnace Peripherals—These include the drive motor and mechanism for the center shaft, furnace combustion air and cooling air fans, spent carbon dewatering and feed equipment at the furnace, fuel system, exhaust gas scrubbing, quench tank, steam boiler and boiler feedwater treatment, furnace control panel, and instrumentation. No detailed specifications on these components were available from the published cost literature.

Direct Capital Cost

Direct capital costs are given in Figure 4-30.

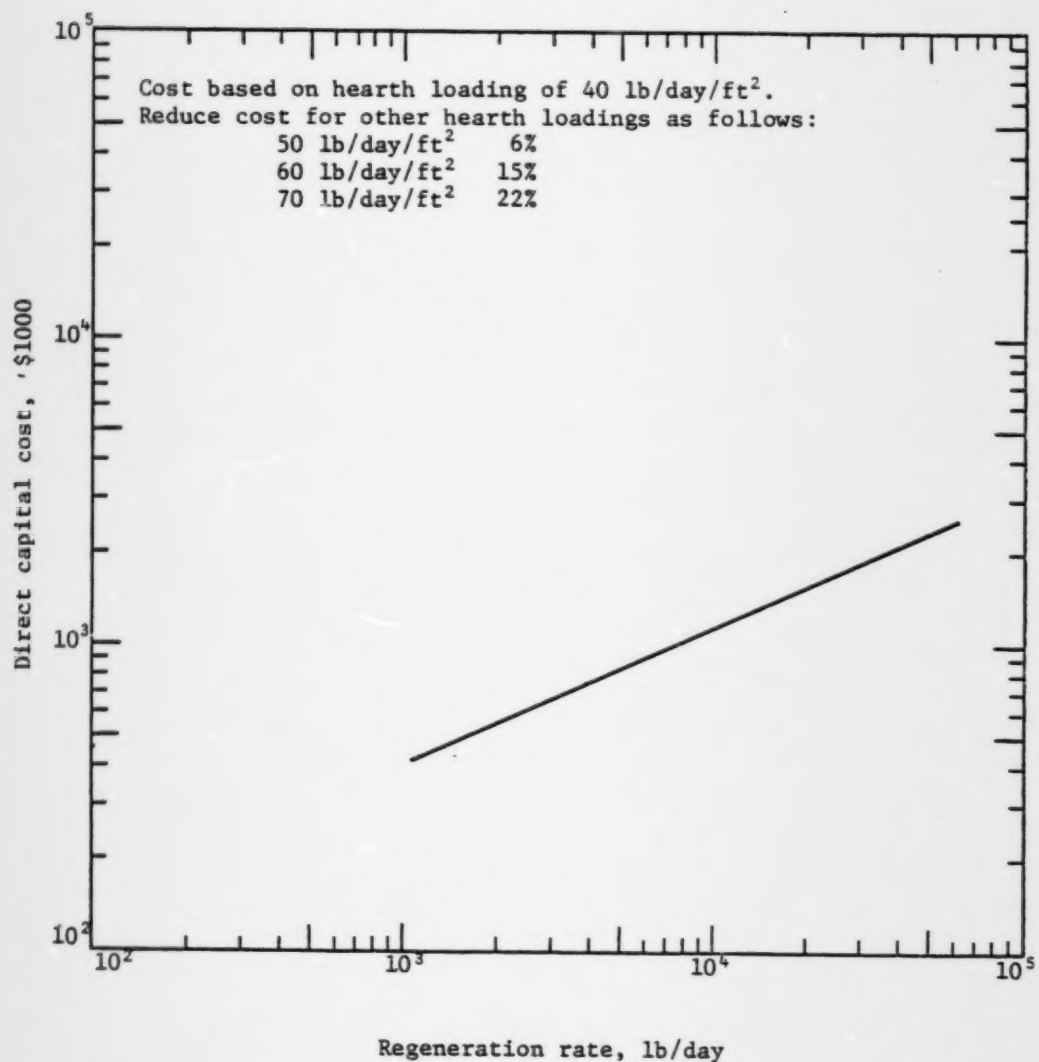


Figure 4-30. Multihearth furnace - direct capital cost.
(September, 1980 dollars)

Operating Requirements

Labor--Variable with 4.0 to 8.0 man-hours per shift as a typical requirement.

Maintenance materials--2 percent of direct capital costs.

Power--.05 kWh/lb of carbon regenerated.

Fuel--3000-5500 Btu/lb of carbon regenerated and fuel to operate the afterburner.

Steam--1.0 lb/lb of carbon regenerated.

Labor specified with the furnace system is that portion of the total operating labor for the activated carbon system estimated to be associated with regeneration activities. Primary maintenance needs are for drive machinery, rabble arms, and refractory replacement or repair.

The electricity requirements listed in current literature vary considerably. The value listed in the preceding table is an approximation of the average requirement. The same is true for the steam requirement. A range of 0.4-3.0 pounds of steam per pound of carbon regenerated is found in the literature.

Processing Expenses

Processing expenses are given in Figure 4-31.

Cost Reference

Capital costs are adjusted and updated from Reference 7. Labor, power, fuel, and steam requirements were also obtained from Reference 7 and updated using prices from Table 5-1 in the present report.

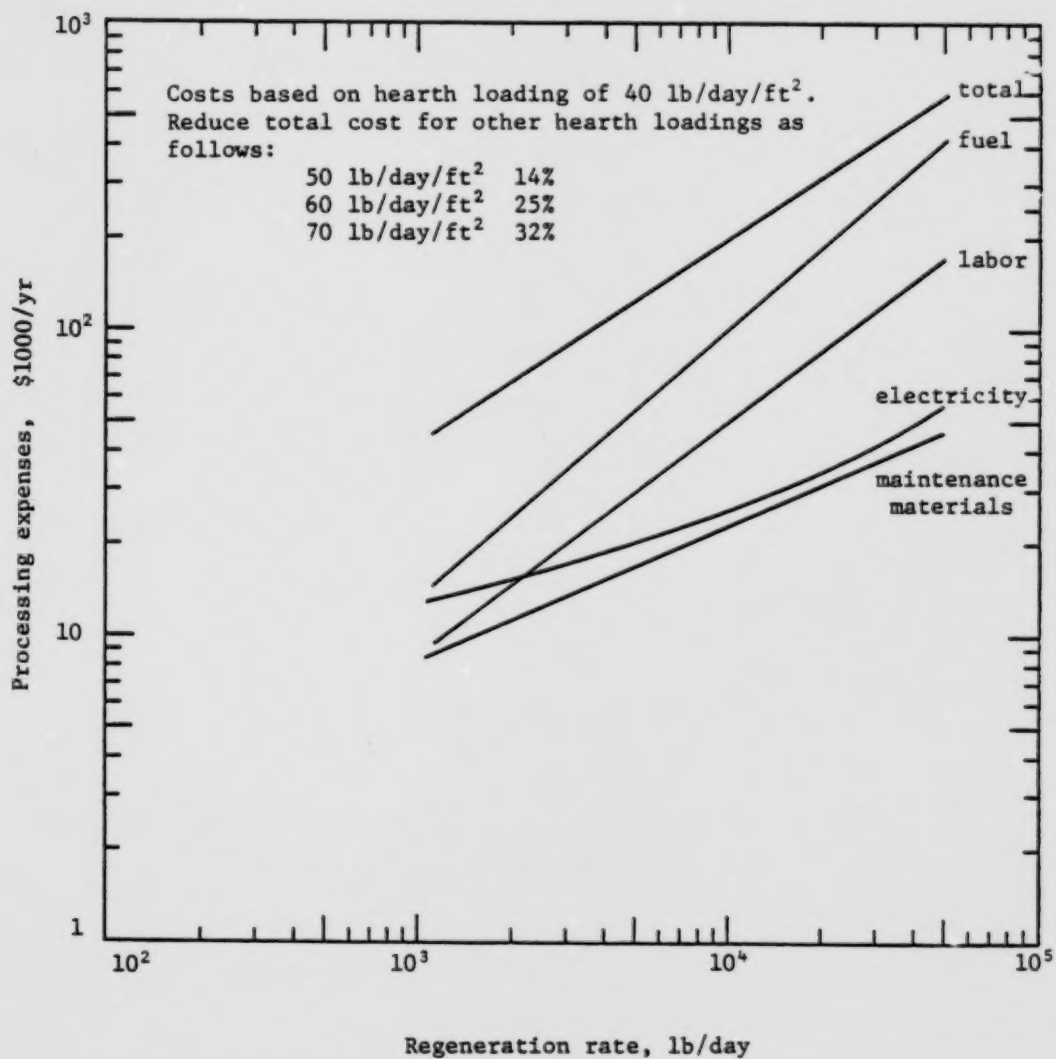


Figure 4-31. Multihearth regeneration furnace - processing expenses.
(September, 1980 dollars)

4.3.2 Fluid-Bed Regeneration Furnaces

Design Basis

Basic Furnace—A view of a fluid bed furnace unit was shown in Figure 3-11. The unit consists of a vertical cylindrical steel housing lined with refractory material and divided into two distinct sections. The upper section is for drying the entering carbon, and the lower section is a higher temperature regeneration zone. Carbon in the regeneration zone is fluidized by the upflow of hot gases from fuel combustion.

The carbon loading for the fluid bed furnace is 70-73 lb/hr/ft² of furnace cross sectional flow area.

Other Components—Other components of the furnace system include carbon dewatering, fluidizing air blower, quench tank, particulate scrubber, interconnecting piping and electrical equipment, controls, and instrumentation.

Direct Capital Cost

Direct capital costs are given in Figure 4-32.

Operating Requirements

Labor—Variable, with less than 4 man-hours per shift possible.

Maintenance Materials—2 percent of direct capital cost.

Power—.05 kWh/lb of carbon regenerated.

Fuel—3000 Btu/lb carbon regenerated.

Steam—0.75 lb/lb carbon regenerated.

Labor includes both operating and maintenance labor. The major maintenance activity is for drive machinery and refractory replacement and repair.

Processing Expenses

Processing expenses are given in Figure 4-33.

Cost Reference

Capital costs were adjusted and updated from Reference 7. Labor, power, fuel, and steam requirements were also obtained from Reference 7 and updated using prices from Table 5-1 in the present report.

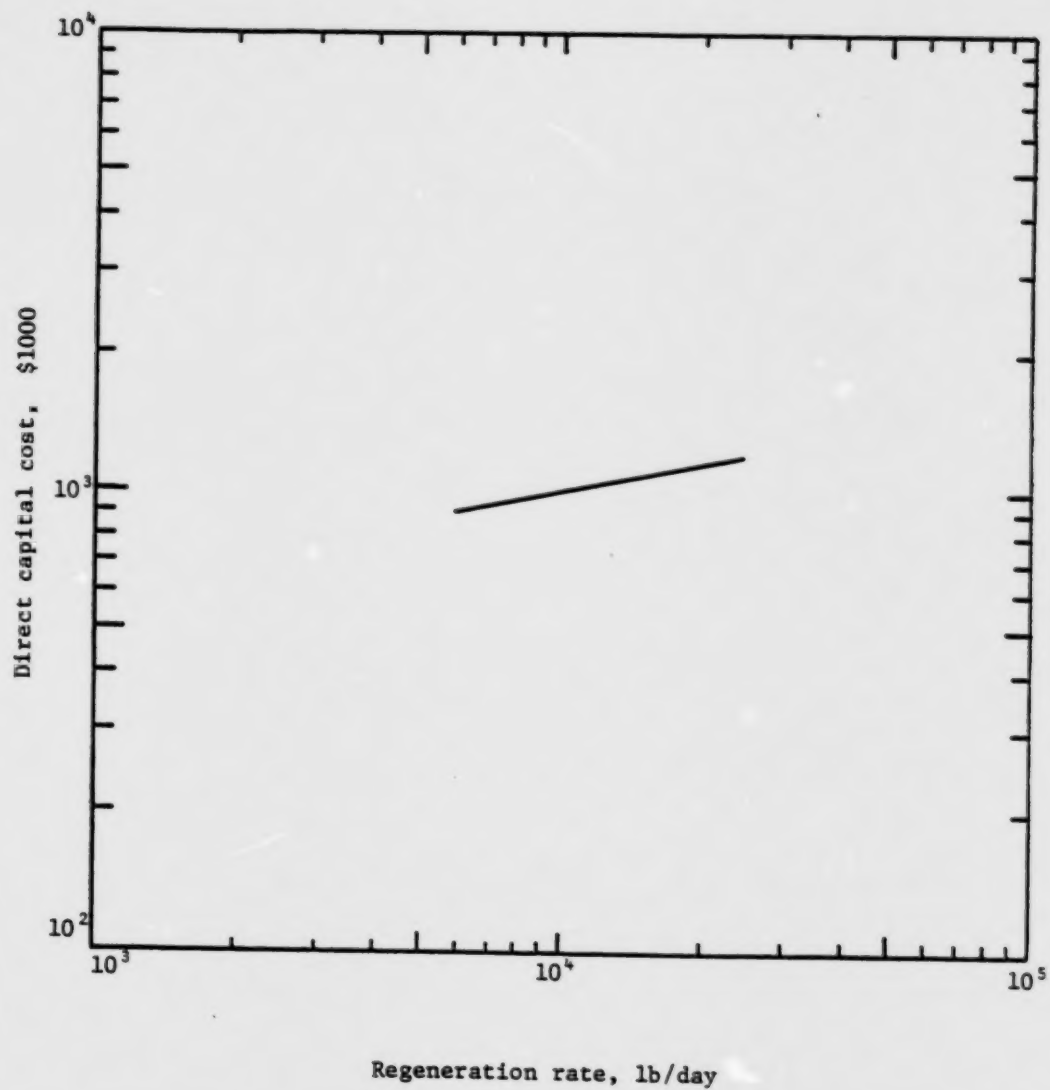


Figure 4-32. Fluid-bed regeneration furnace - direct capital cost.
(September, 1980 dollars)

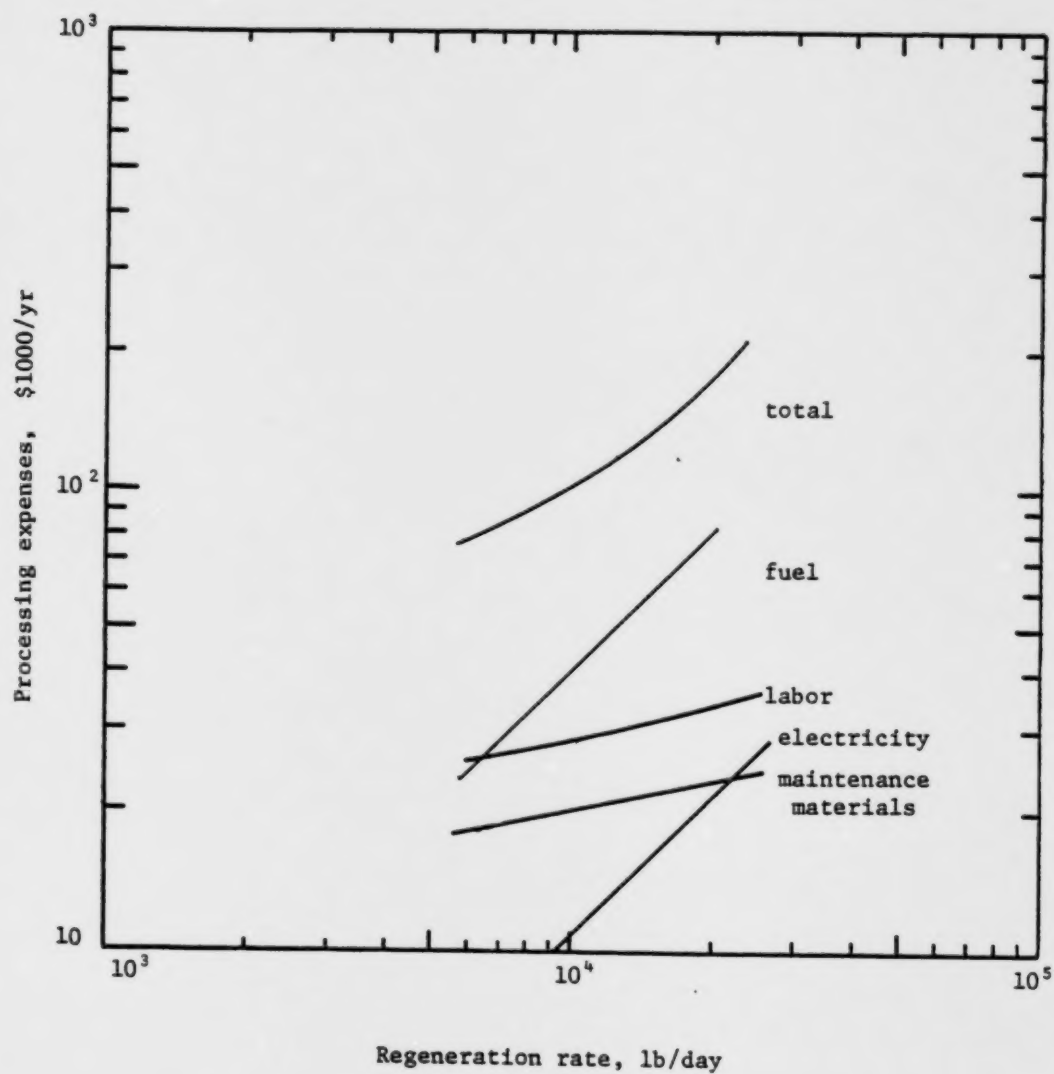


Figure 4-33. Fluid-bed regeneration furnace - processing expenses.
(September, 1980 dollars)

4.3.3 Infrared Regeneration Furnaces

Design Basis

Basic Furnace—The infrared regeneration furnace consists of a heated tunnel through which granular carbon is conveyed by specially-designed belt conveyor. This type of system was shown in Figure 3-12. Infrared heating elements are mounted in the ceiling of the tunnel. Proper performance relies on carbon depth, belt speed control and control of the furnace atmosphere. Different capacities are achieved by combining standard furnace modules. Furnace dimensions range from 4 ft wide to 20 ft long to 10 ft wide by 123 ft long. Capacities range from 2400 to 90,000 lb/day of carbon.

Feed Screw—The feed screw is of the same type used for other regeneration equipment.

Quench Tank—The quench tank is of the same type used for other regeneration equipment.

Afterburner—A flue gas afterburner unit is employed on the furnace stack.

Air Pollution Abatement System—This comprises a wet scrubber, valving, piping, pumps, and blower comparable to such systems on other regeneration furnaces.

Controls and Instrumentation—These include electrical items for both the basic furnace unit and peripherals.

Direct Capital Cost

Direct capital costs are given in Figure 4-34.

Operating Requirements

Labor—Variable with 8 man-hours per shift a typical requirement.

Maintenance Materials—2 percent of direct capital cost. A major maintenance requirement is replacement of the quartz heating units which have a life expectancy of about 5000 hours.

Power—1.6 kWh/lb of carbon regenerated.

Process Water—0.5 gal/lb of carbon processed. This water is for the scrubbing system.

Processing Expenses

Processing expenses are given in Figure 4-35.

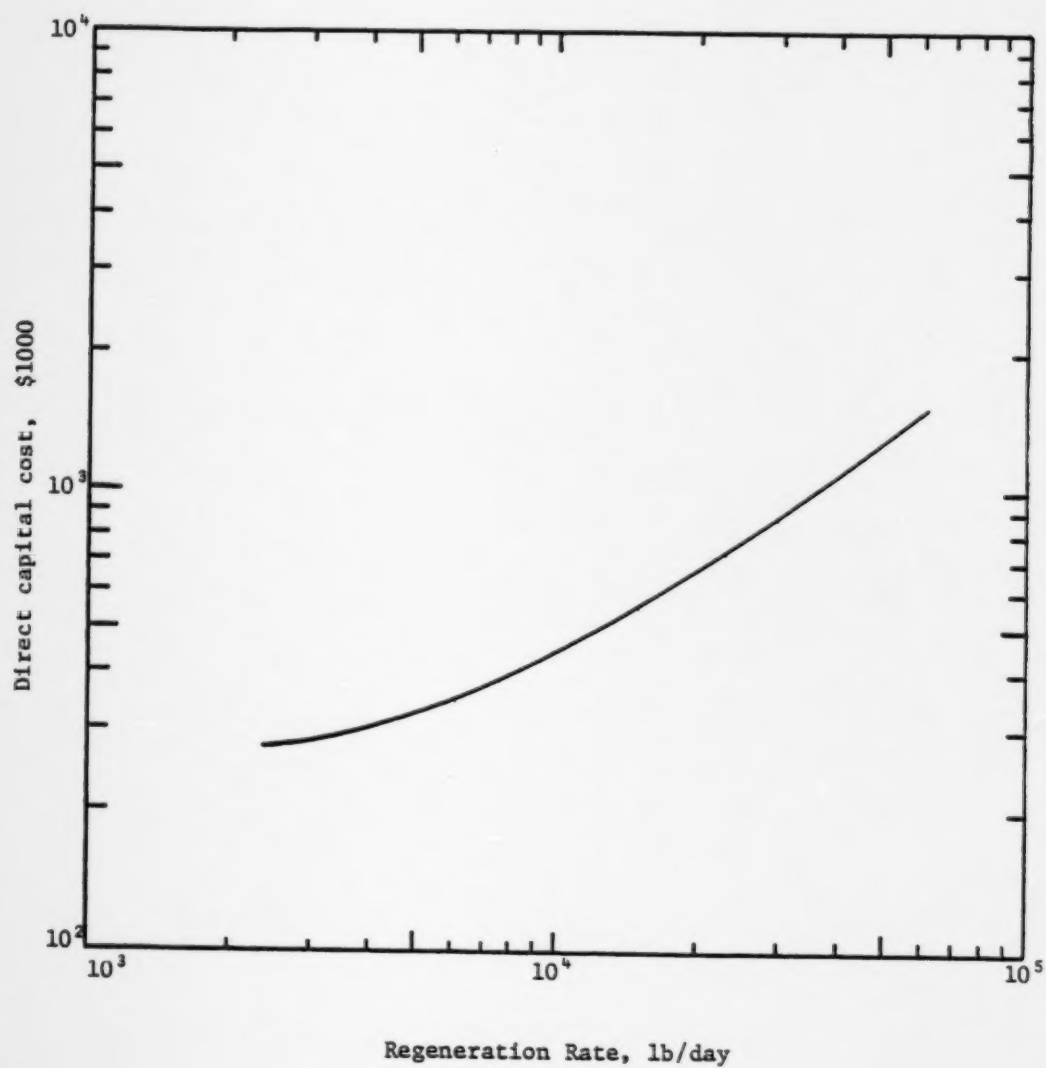


Figure 4-34. Infrared regeneration furnace - direct capital cost.
(September, 1980 dollars)

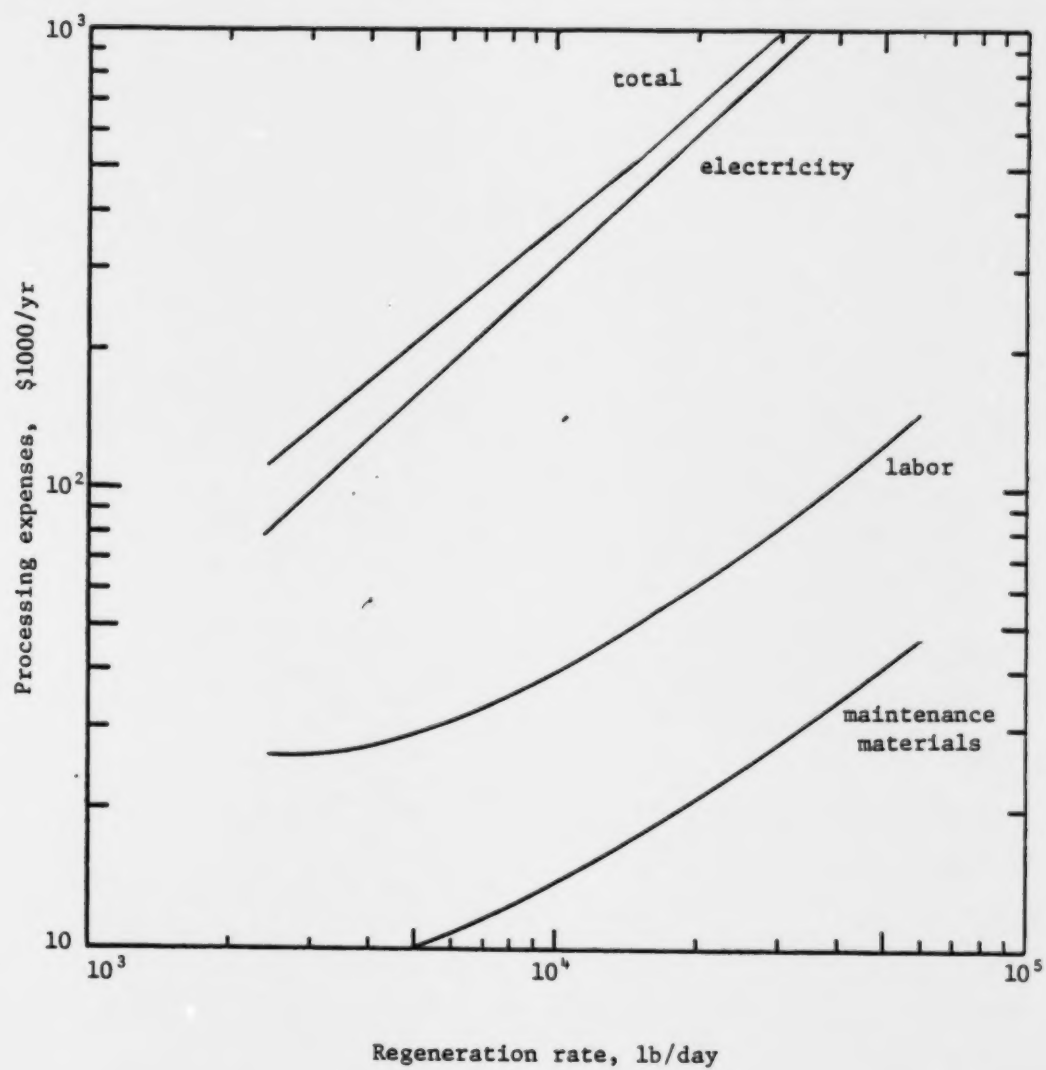


Figure 4-35. Infrared regeneration furnace - processing expenses.
(September, 1980 dollars)

Cost References

Capital costs were adjusted and updated from Reference 7. Labor, power, and process water requirements were also obtained from Reference 7 and updated using prices from Table 5-1 in the present report.

4.3.4 Off-Site Regeneration^a

Design Basis

Off-site regeneration usually involves truck handling of spent carbon from a plant to a regional regeneration facility by a second party for a negotiated fee. This is considered in cases where it is not economically feasible to install on-site regeneration equipment. A regional facility will usually service a number of water treatment plants within a distance of up to 100 miles. The spent carbon is dewatered and then stored at the treatment plant. Trucks will periodically haul an amount of carbon to the central location where it is regenerated separately from other carbons. A delivery is then made to the treatment plant with freshly regenerated carbon.

Direct Capital Cost

Direct capital costs associated with this option can be estimated from the carbon storage and transfer module.

Operating Requirements

Operating requirements other than the contractor fee depend on the specific agreement between operating facility and the contractor.

Processing Expenses

Processing expenses are given in Figure 4-36.

Cost Reference

Costs were adjusted and updated from Reference 7.

4.4 AUXILIARY EQUIPMENT AND OFF-SITES

Process auxiliaries and off-sites include equipment, structures, and operating needs not identified as part of the other three subsystems in a GAC plant. This category includes both modules of equipment as well as individual equipment items.

Auxiliaries and off-sites in this section are:

- the influent pump station,

^aA variation of this option is to contract for a complete service to provide carbon adsorption treatment. At least one major manufacturer of activated carbon provides this service. Costs in this section do not apply to such service.

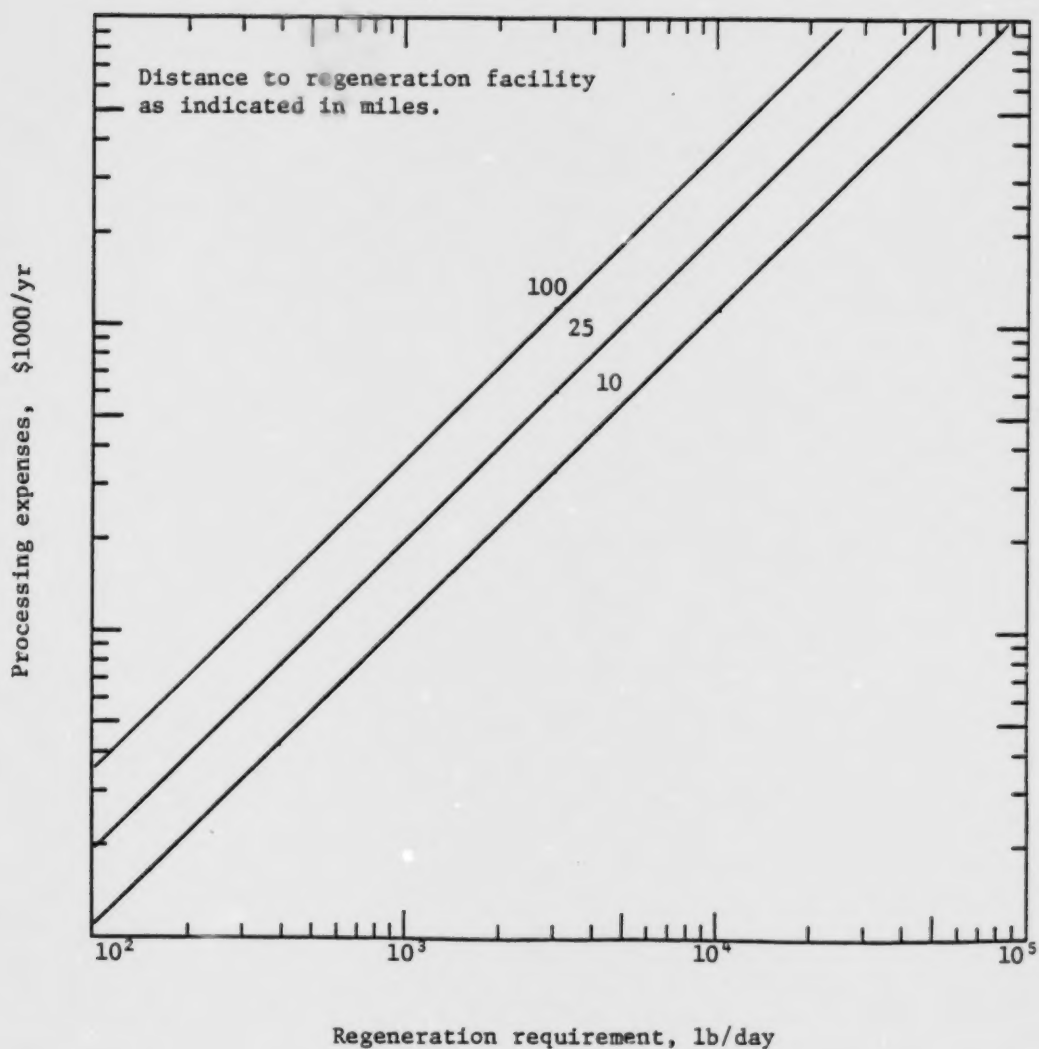


Figure 4-36. Off-site regeneration - processing expenses.
(September, 1980 dollars)

- unit piping and valves,
- electrical power supply and distribution,
- site preparation, and
- buildings.

4.4.1 Influent Pump Station

Design Basis

Pumps are the constant speed, electrically driven centrifugal type. Total dynamic head ranges from 40-100 ft. Pump costs include motor starters and other electrical controls. Two operating pumps each sized at one-half design flow are provided up to a maximum individual pump flow rate of 7000 gpm. Above this, flow rate multiple pumps are provided as required to meet total design flow. One spare pump is provided.

Piping and valves needed to connect the pumps to common inlet and outlet piping manifolds are included. Costs were calculated as a fraction of the purchased equipment costs for pumps and drivers (See Appendix D).

Direct Capital Costs

Direct capital costs are given in Figure 4-37 for several different pumping heads.

Operating Requirements and Processing Expenses---

Labor—The labor requirement varies with system size. Labor includes operation and maintenance of the pumps, motors, electrical controls, and valving. Typical labor hours at several plant flow rates are:

<u>Flow rate (mgd)</u>	<u>Labor (hrs/shift)</u>
1	0.5
10	0.7
100	2.4

Maintenance Materials—2 percent of direct capital cost.

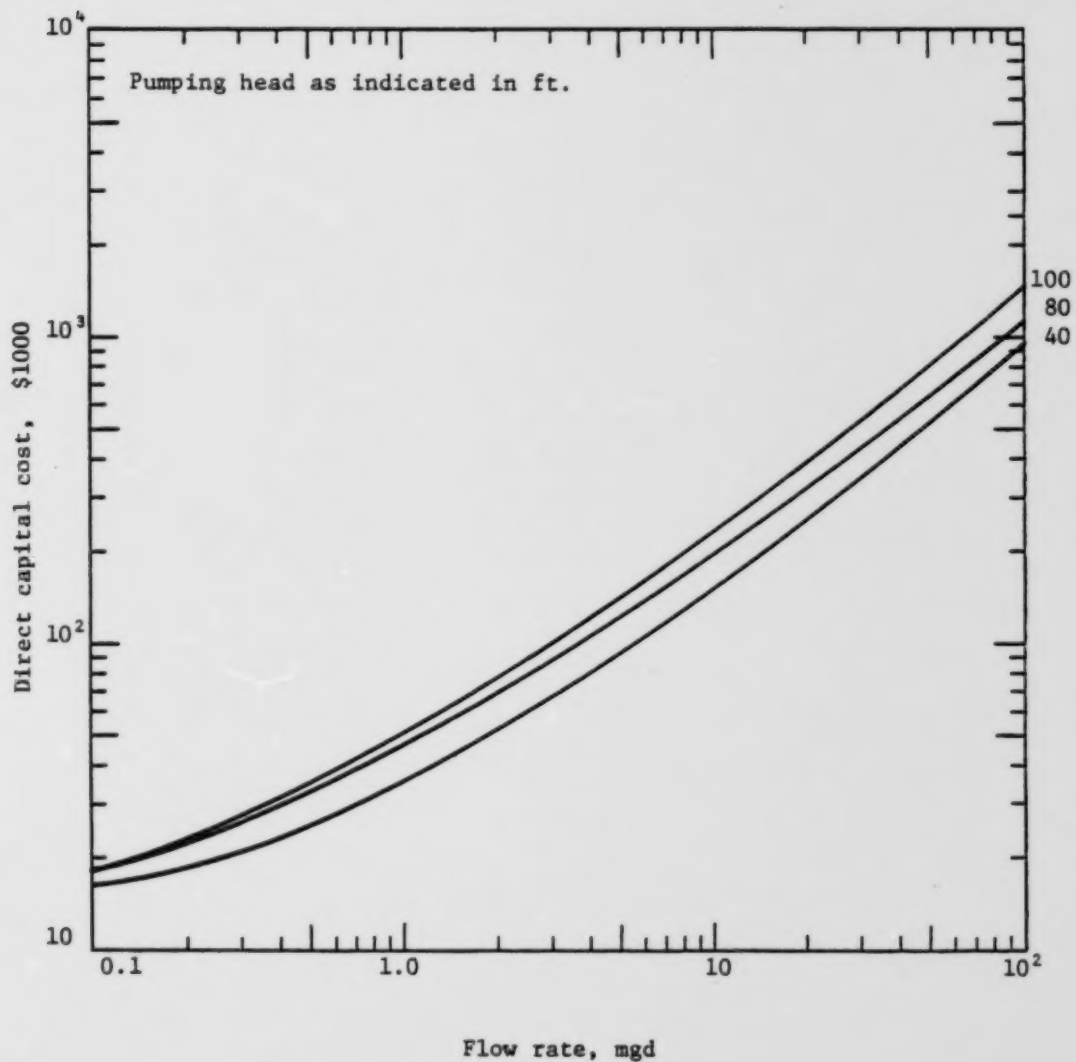


Figure 4-37. Influent pump station - direct capital cost.
(September, 1980 dollars)

Power^a—Power needs depend on pumping head requirement and efficiency. At 60 percent efficiency power requirement at various heads is:

<u>Head (ft)</u>	<u>Power (kW/mgd)</u>
40	8.9
60	13.4
80	17.8
100	22.2

Processing Expenses

Processing expenses are given in Figure 4-38 for several different pumping heads.

Cost References

Pump costs including peripheral equipment (e.g. piping, electrical, etc.) were obtained from Reference 4. Sump costs were based on estimates for small concrete vessels using estimating procedures in Reference 2.

$$0.75 \times \text{gpm} \times \text{psi}$$

^a Pumping power is calculated from: $\text{kW} =$

$$1714 \times e$$

where gpm = flow rate in gallons per minute

psi = discharge pressure in pounds per square inch corresponding to head requirement.

e = pump and motor combined efficiency; a value of 0.6 is used in this report.

1714 = a conversion factor between English units of measure.

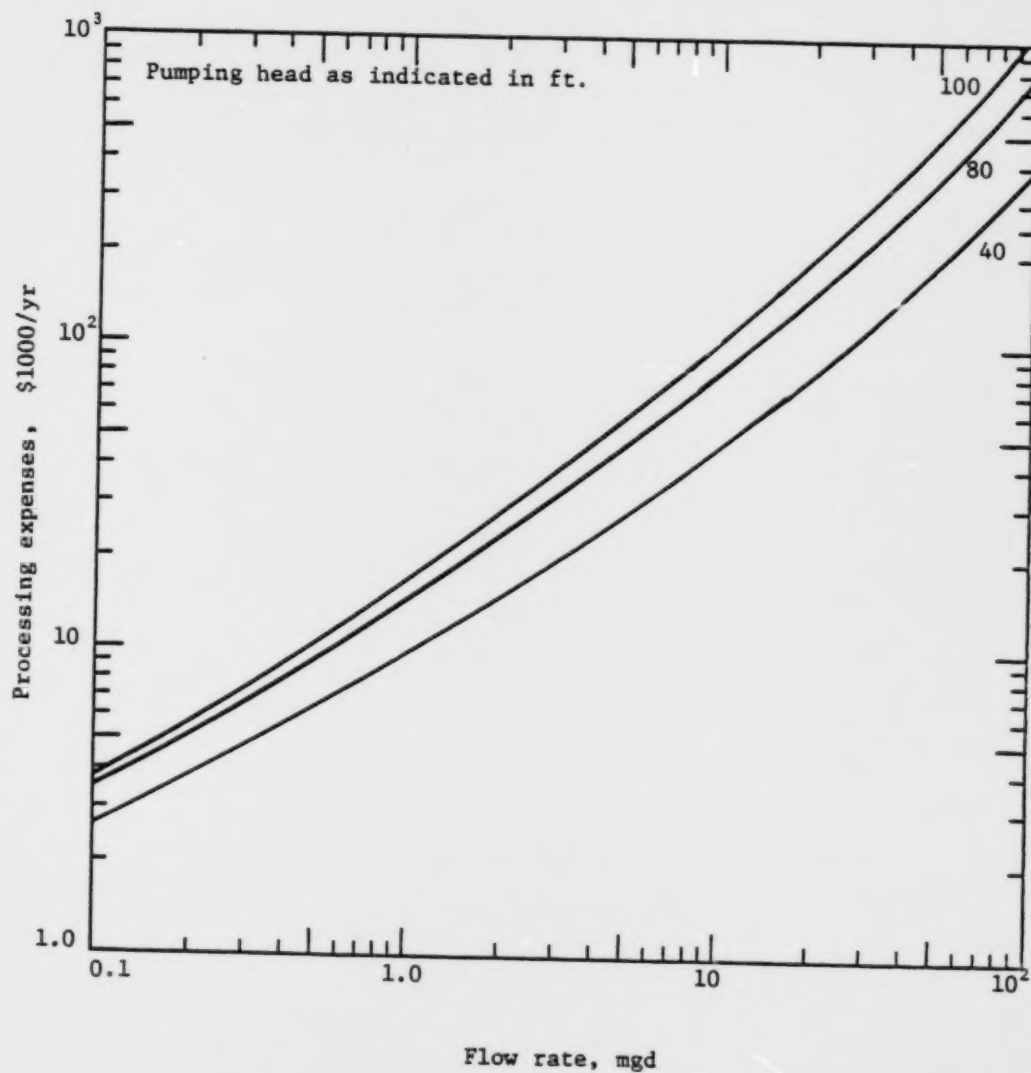


Figure 4-38. Influent pump station - processing expenses.
(September, 1980 dollars)

4.4.2 Unit Piping and Valves

Unit piping is used for interconnecting major process modules and for connecting the GAC system with other parts of an overall treatment plant. These same unit piping costs were used to estimate costs for piping directly associated with adsorbers.

Design Basis

Costs for field-installed carbon steel and stainless steel pipe are presented in Table 4-1. The costs are for Schedule 40 pipe and include a typical mix of flanges and fittings. Two types of piping arrangements specified are "simple" and "complex" reflecting the number of interconnections and fittings per average run. For interconnecting piping it is appropriate to use the "simple" designation. Piping associated with most vessels would fall under the "complex" category.

Field installed costs for carbon steel and stainless steel manual gate valves are presented in Table 4-2. The valves are rated for 150 psig. Gate valves are given here as representative of all valves in a GAC plant. In fact, GAC systems use a variety of valves depending on the specific use of the valve within the system.

Pipe insulation installed costs are presented in Table 4-3. Insulation might be required for systems in cold climates.

Direct capital costs for underground carbon steel piping and cast iron sewer piping are presented in Table 4-4. Costs include fittings, flanges, hub joints, trenching and backfilling.

Typically, piping costs for GAC plants range from 20 to over 100 percent of the other capital equipment costs, depending on the material of construction, piping run lengths, type of valves, and valve mix used. The unit pipe costs in this module were the basis for estimating costs of piping associated with storage vessels and adsorbers discussed earlier. For storage vessels and adsorbers, associated piping costs were estimated using a take-off on several conceptual piping system designs to establish appropriate piping factors applied to vessels of different sizes specific to GAC systems as conceived in this report.

An approximate guide to line and valve sizing based on flow rate is given in Table 4-5. This table is used to determine sizes when flow rate is known.

Operating Requirements

Labor and maintenance materials associated with piping portions of a GAC system are included in the process module of which the piping is a part.

TABLE 4-1. UNIT PIPING-DIRECT CAPITAL COST^a (September 1980 Dollars)

Pipe Diameter (inches)	Direct Capital Cost (\$/ft)			
	Carbon Steel		Stainless Steel	
	Simple	Complex	Simple	Complex
1	3.00	5.00	10.00	13.00
2	6.00	10.00	22.20	29.50
3	9.20	15.50	36.00	47.50
4	12.50	21.00	50.00	67.00
6	19.00	32.00	80.00	109.00
8	25.50	45.00	112.00	155.00
10	32.20	59.00	145.00	212.00
12	39.00	78.00	180.00	280.00
14	47.50	98.00	220.00	—
18	66.00	155.00	300.00	—
24	100.00	270.00	—	—

^aCosts are based on standard complements of straight pipe and fittings define as either simple or complex configurations. A complex configuration reflects the kind of piping associated with adsorber vessels and a simple configuration the kind associated with storage tanks, interconnecting, or offsite piping. Costs are derived from straight piping, and pipe fitting capital costs in Reference 4.

TABLE 4-2. UNIT VALVE - DIRECT CAPITAL COST^a (September, 1980 Dollars)

Valve Size (Inches)	Manual Gate Valves (\$/ea)	
	Carbon Steel	Stainless Steel
1	340	580
2	430	1150
3	520	1700
4	640	2200
6	950	3400
8	1450	5000
10	2400	7000
12	3300	9800
14	4700	13000
16	6300	—
18	8000	—
24	15000	—

^aCosts are derived from costs for manual gate valves in Reference 4.

TABLE 4-3. PIPE INSULATION - DIRECT CAPITAL COST^a
(September, 1980 Dollars)

Pipe Diameter	Insulation Cost (\$/ft)		
	Thickness: 1 inch	2 inch	3 inch
2	7.30	11.70	18.90
2.5	8.30	13.30	21.70
3	9.30	15.00	23.90
4	11.00	17.80	28.90
6	14.00	23.30	35.00
8	17.20	28.90	45.00
10	20.00	35.00	53.30
12	23.30	38.90	62.20
14	26.60	44.40	71.00
16	30.00	51.10	80.00
18	31.40	61.00	88.80
20	38.90	66.60	97.70
24	51.00	83.30	133.00

^aCosts are derived from Reference 4.

TABLE 4-4. UNDERGROUND PIPE - DIRECT CAPITAL COST^a
(September, 1980 Dollars)

Pipe Diameter (inches)	Direct Capital Cost (\$/ft)	
	Carbon Steel	Cast Iron
2	25.00	—
2.5	25.50	—
3	26.10	—
4	26.60	17.20
6	30.00	23.90
8	35.50	32.20
10	42.20	41.10
12	47.70	53.30
14	57.70	66.60
16	63.30	77.70
18	71.00	92.10
20	73.30	108.00
24	79.90	139.00

^aCosts are derived from Reference 4.

TABLE 4-5. ECONOMICAL PIPE DIAMETER FOR VARIOUS FLOW RATE RANGES^a

Flow Rate (gpm)	Nominal Pipe Diameter (inches)
<15	1.0
15-30	1.5
30-60	2.0
60-125	3.0
125-250	4.0
250-500	6.0
500-900	8.0
900-1500	10.0
1500-2000	12.0
2000-3000	14.0
3000-4000	16.0
4000-5000	18.0
>5000	24.0

^aAdapted from Reference 14.

Processing Expenses

Annual expenses, mostly for maintenance, associated with interconnecting and offsite piping are negligible in the context of other processing expenses.

Cost Reference

Piping and valve costs were derived from Reference 4.

4.4.3 Electrical Power Supply and Distribution

Design Basis

Electrical power supply and distribution costs are very site-specific and must be included in costs for GAC systems unless adequate power is known to be available at a system size. Costs include equipment for substations and associated electrical items.

Direct Capital Cost

Figure 4-39 shows direct capital costs for the electrical component items discussed above.

Operating Requirements

Maintenance is required.

Processing Expenses

Maintenance materials and labor may be taken as one percent of direct capital cost.

Cost Reference

Costs are derived from costs in Reference 18.

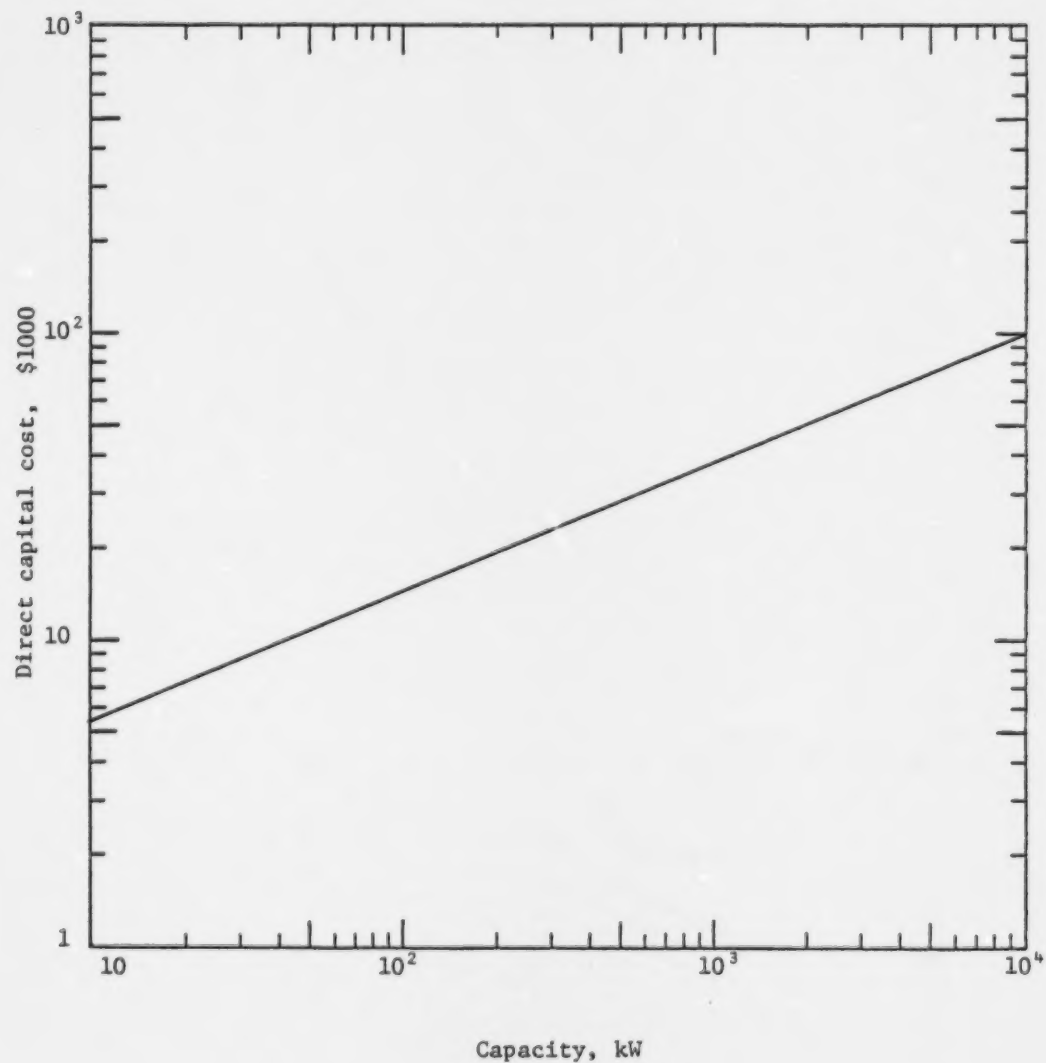


Figure 4-39. Electrical supply and distribution - direct capital cost. (September, 1980 dollars)

4.4.4 Site Development and Land Requirements

Site development costs for GAC systems will be somewhat less of a percentage of total plant cost for grass roots projects if the system is installed as part of an overall treatment system or at an existing plant site.

Site development costs include:

- dewatering and drainage;
- fencing;
- fire protection;
- land surveys and fees;
- landscaping;
- piling;
- roads, walkways, paving;
- parking lots;
- sewers and drainage facilities; and
- site clearing, excavation, and grading.

These costs depend primarily on land area rather than process details. Where the process does use concrete extensively, however, costs for excavation and grading might be higher than for other plants.

Within each of the above categories there are numerous choices which will significantly affect the costs for a given land area. In this report costs were developed for areas of up to two acres using the design specifications listed in Table 4-6.

Land area requirements have been estimated for major process modules and are presented in Figures 4-40 through 4-45. The total land area required for the process modules is obtained by adding the appropriate individual areas. Additional area allowances can be added to account for intermodular spacing, and special site-specific area needs.

Once the land area requirements have been determined, site preparation direct capital costs can be obtained from Figure 4-46.

TABLE 4-6. DESIGN BASIS FOR SITE DEVELOPMENT COSTS^a

Item	Cost and Basis
1. Dewatering and Drainage	\$2.40 per linear foot. Drainage trench with length equivalent one-half the perimeter of land area.
2. Fencing	\$25.00 per linear foot. Chain link fence with length equivalent to one-half of perimeter of land area.
3. Fire Protection	None; assumed available from other portions of facility where GAC plant is being installed.
4. Land Surveys and Fees	\$1,250
5. Landscaping	\$5.00 per square yard for 5% of land area.
6. Piling, ^b concrete cast in place	\$18.00 per linear foot. None used.
7. Roads, Walkways, Paving	4 inch concrete at \$20 per square yard. Area is 5% of land area.
8. Parking Lot, Roads	Black top at \$16.00 per square yard. Area is 28 square yards.
9. Sewer and Drainage Facilities	18 inch concrete pipe, length equal to land area perimeter. \$16.00 per linear foot.
10. Site Clearing Excavation and Grading	Total land area assumed for grading, and one-half of land area for excavation to average depth of five feet. Site clearing and grading - \$2.90 per square yard Excavation - \$21.00 per cubic yard

^aCosts updated from Reference 4.

^bRequired only for some sites depending on soil conditions.

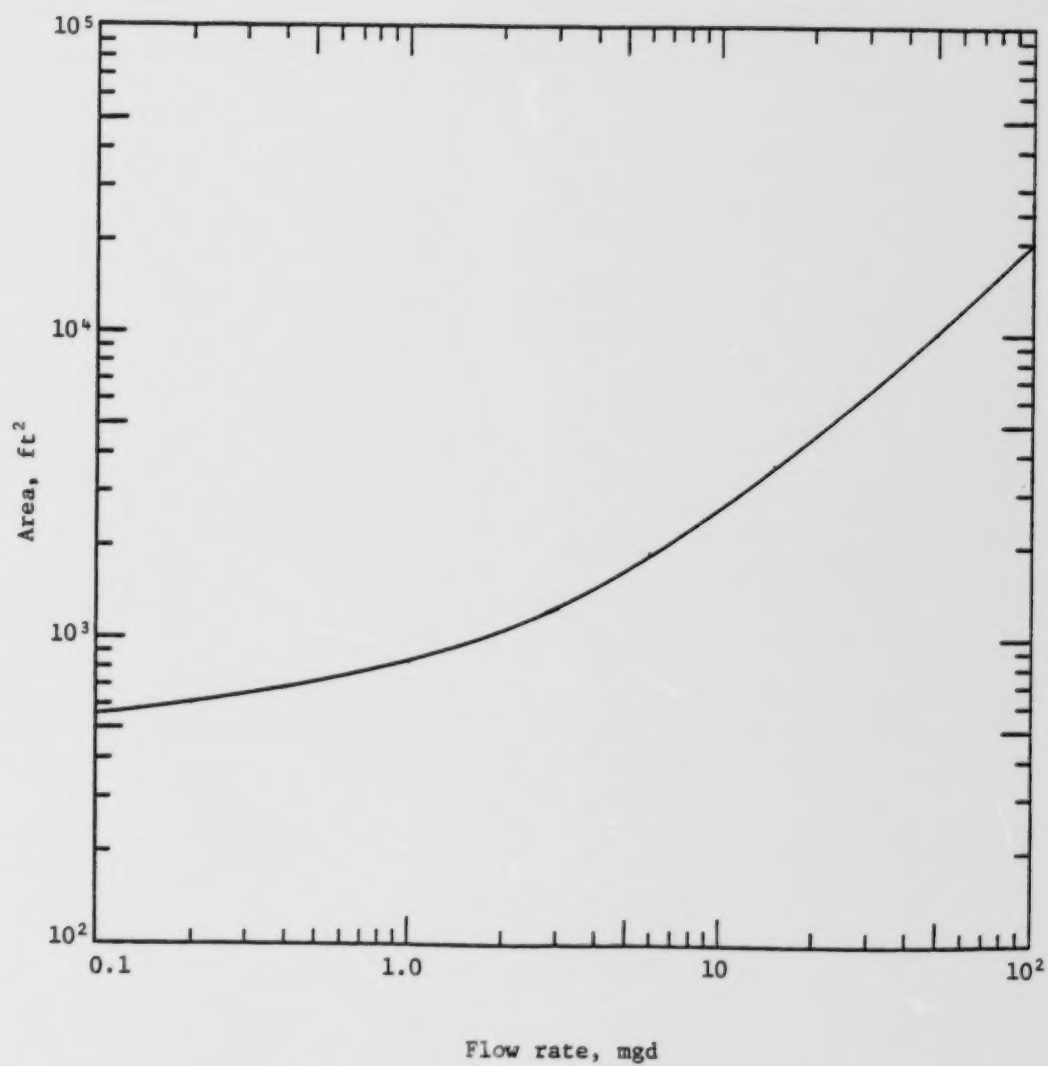


Figure 4-40. Influent pump station area.

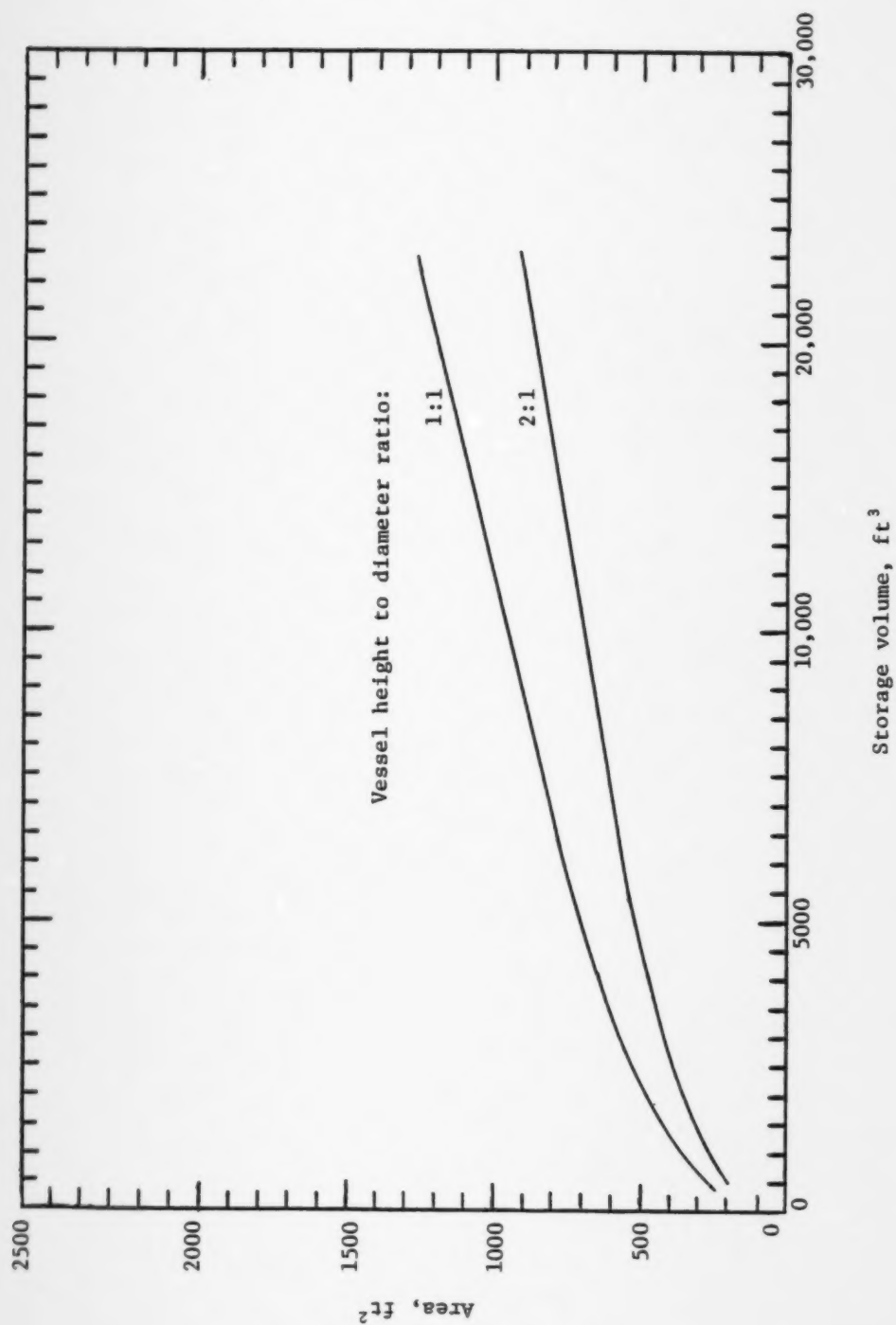


Figure 4-41. Carbon storage and transfer module area.

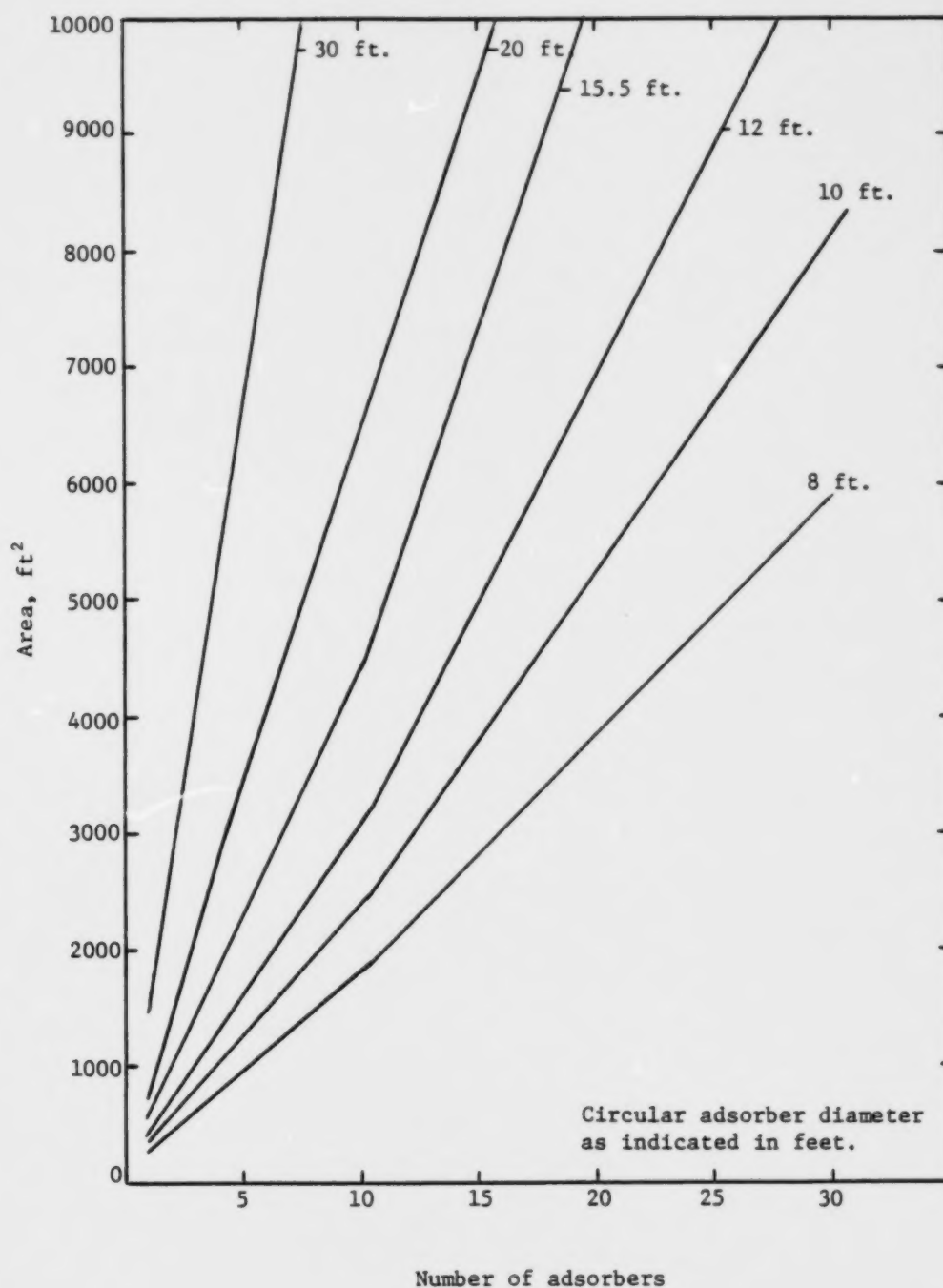


Figure 4-42. Steel adsorber module area.

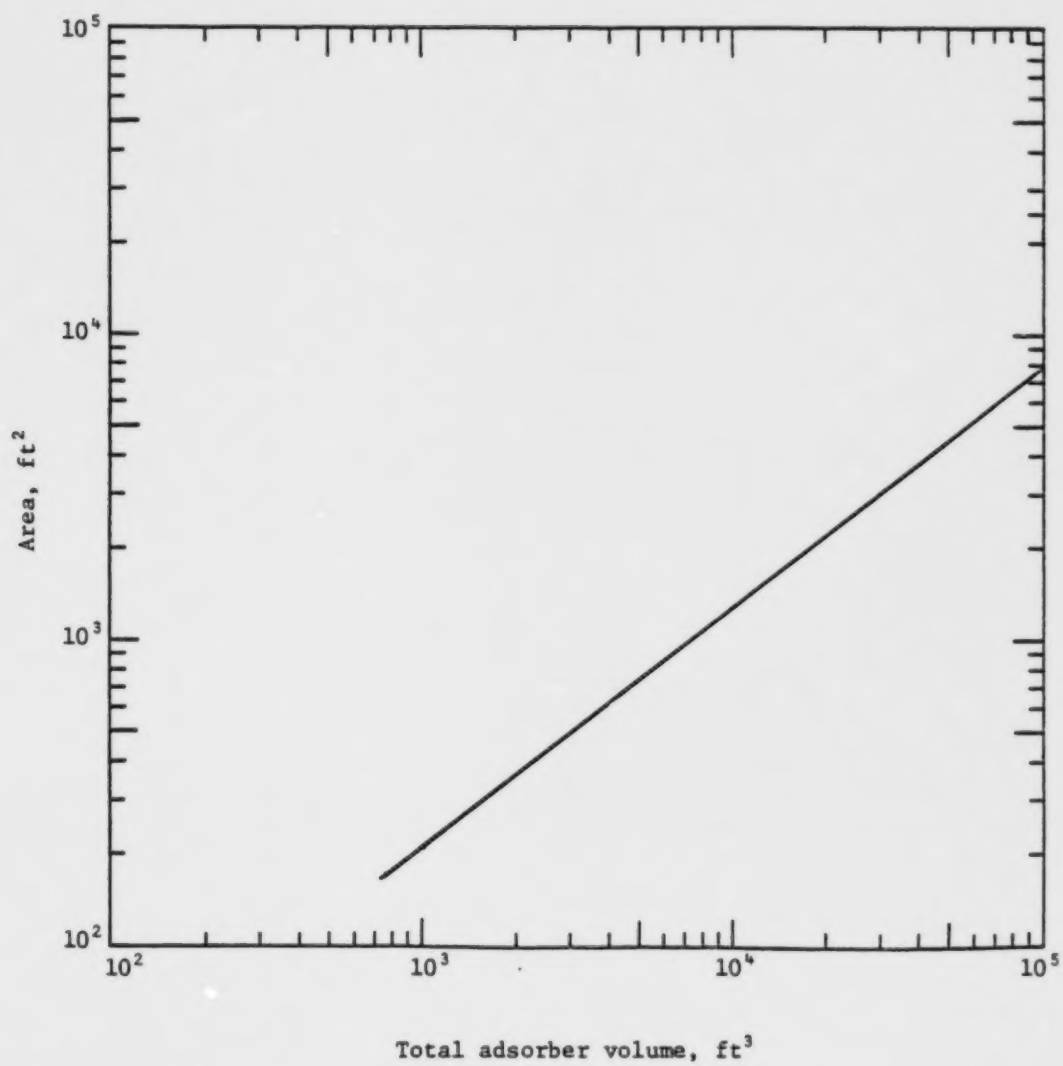


Figure 4-43. Concrete adsorber module area.

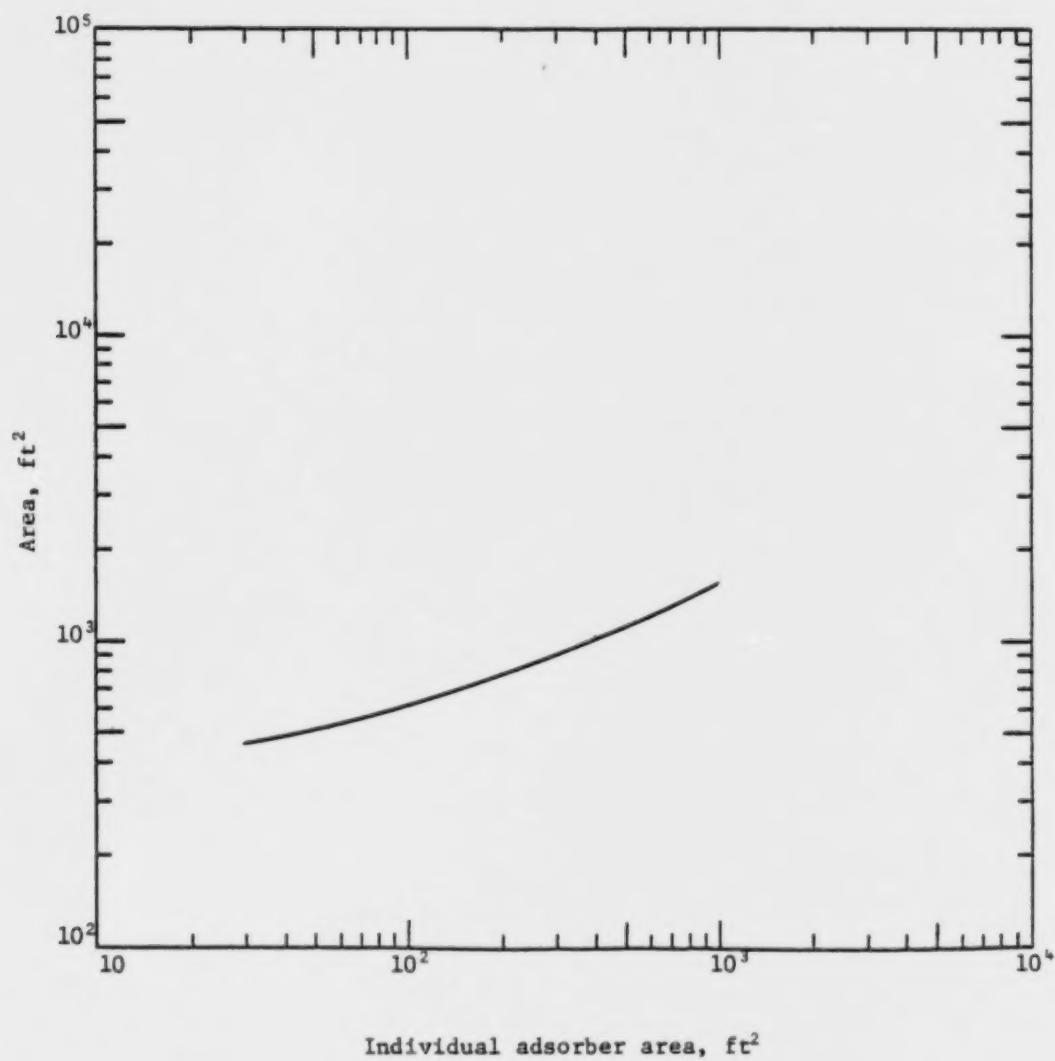


Figure 4-44. Backwash module area.

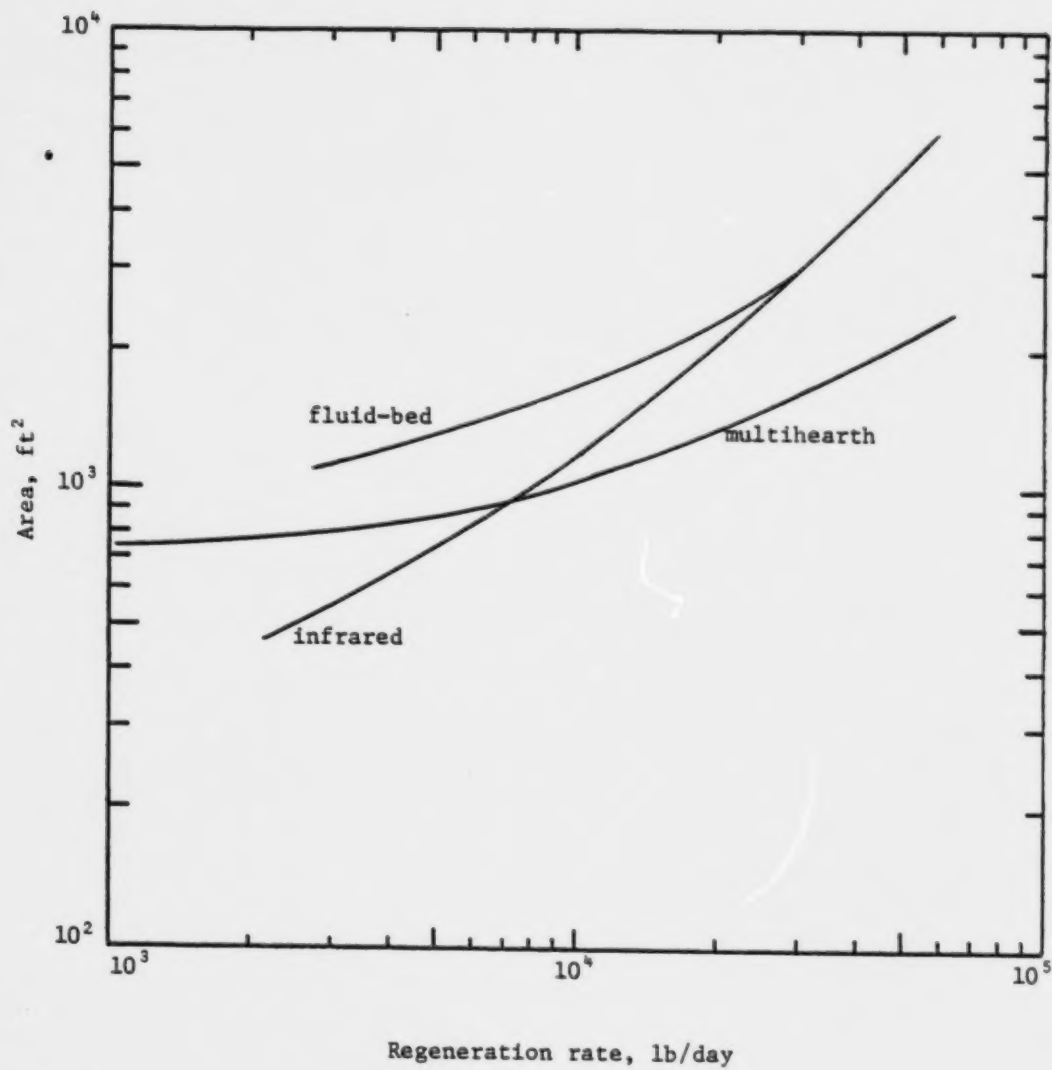


Figure 4-45. Regeneration system area.

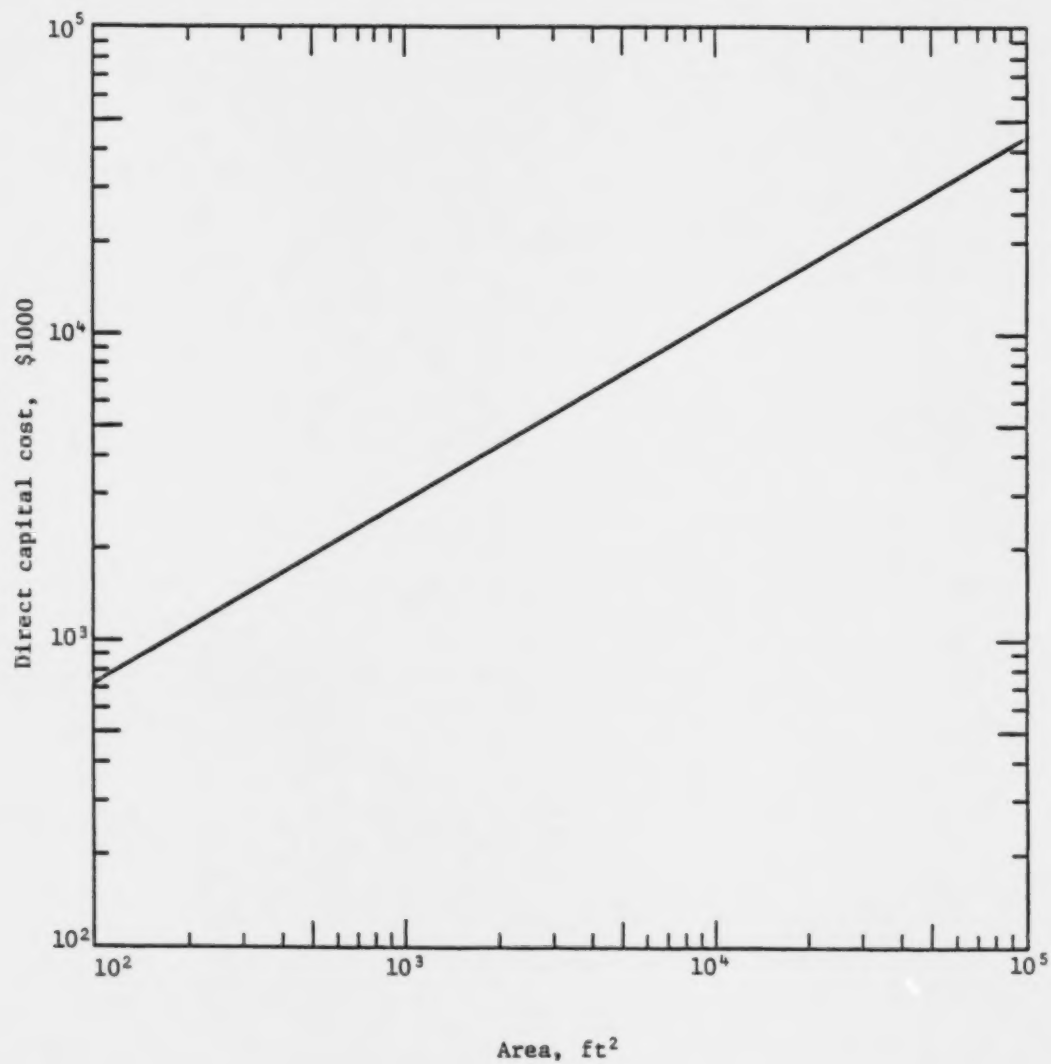


Figure 4-46. Site preparation - direct capital cost.
(September, 1980 dollars)

4.4.5 Buildings

Design Basis

Process building costs are site-specific and are dependent on:

- type of construction (e.g. prefabricated, cement block, brick, etc.,
- type of foundation,
- heating, ventilation, air conditions, and lighting requirements, and
- size of building.

Direct capital costs for a medium steel frame building are presented in Figure 4-47. These costs include steel frame, brick or concrete walls, concrete floor and roof, and average heating, lighting, and ventilation facilities^a. Figures 4-40 through 4-46 can be used as an aid to estimating area requirements for housing process equipment.

Operating Requirements

Maintenance Materials and Labor—Materials and labor for building maintenance are taken as 2% of direct capital cost.

Power—Power requirements cover energy needs for heating, ventilation, air conditioning, and lighting. These requirements for buildings can range from as little as 10 kWh per square foot per year to as high as 220 kWh per square foot per year, depending on area climate conditions.

Table 4-7 presents a summary of these power requirements for 21 U.S. cities (7).

Processing Expenses

Processing expenses can be estimated from the above operating requirements.

^aBuilding costs are highly variable and site-specific. The costs presented here are for general use if more specific information on building costs is not available to the user. Generalized costs for industrial buildings are available in a number of sources.

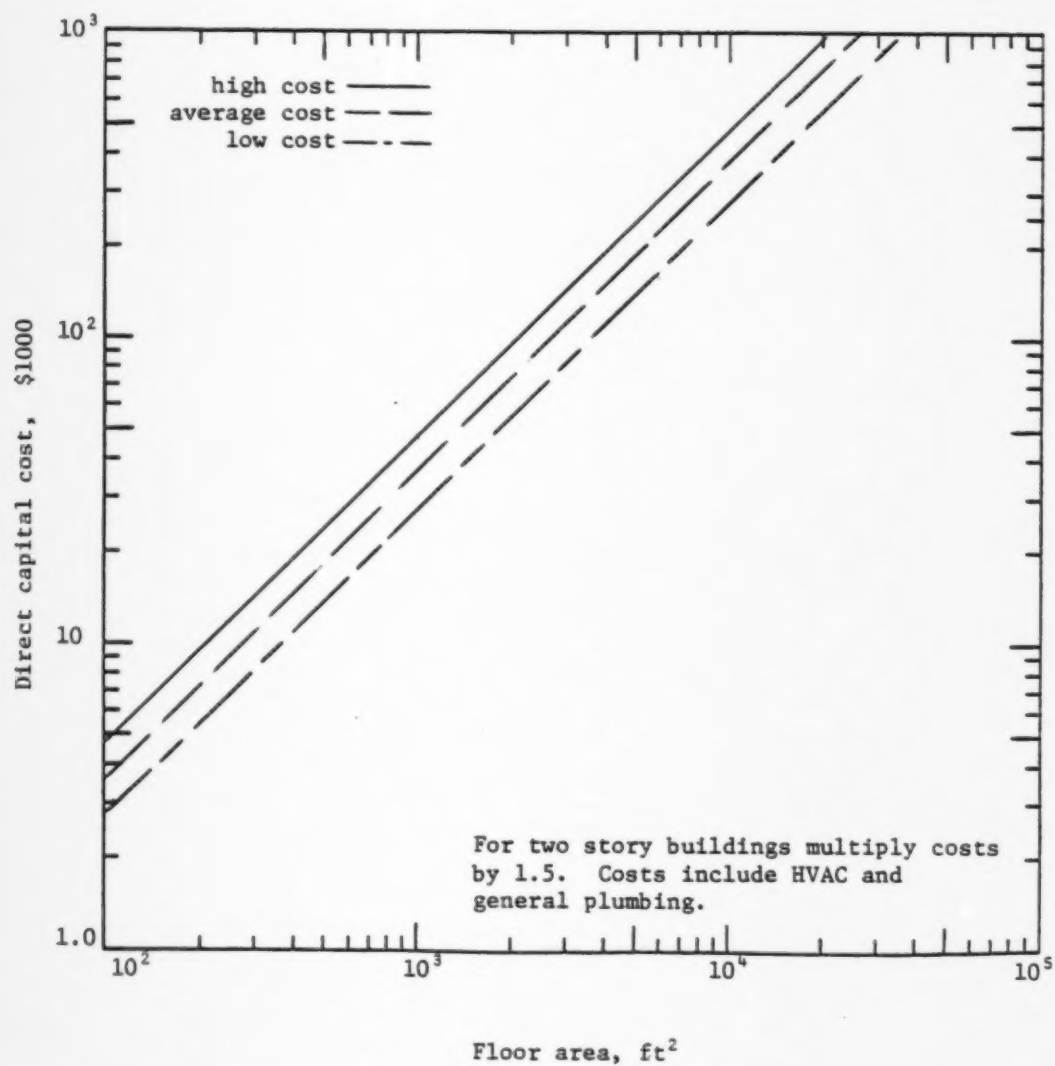


Figure 4-47. Buildings - direct capital cost.
(September, 1980 dollars)

TABLE 4-7. GEOGRAPHICAL INFLUENCE UPON BUILDING-RELATED ENERGY

City	Electrical Energy - kWh/ft ² /yr				Total
	Lighting	Ventilation	Heating	Cooling	
Seattle	17.5	2.2	59.4	0.2	79.3
Salt Lake City	17.5	2.2	144.0	0.8	164.5
Omaha	17.5	2.2	157.3	0.9	177.9
Minneapolis	17.5	2.2	199.4	0.7	219.8
Chicago	17.5	2.2	146.4	0.8	166.9
New York	17.5	2.2	90.3	0.7	110.7
Boston	17.5	2.2	104.4	0.4	124.5
San Francisco	17.5	2.2	40.5	0.5	60.7
Denver	17.5	2.2	149.5	1.6	170.8
St. Louis	17.5	2.2	116.6	2.4	138.7
Las Vegas	17.5	2.2	36.3	2.4	58.4
Richmond, VA	17.5	2.2	71.6	1.6	92.9
Nashville	17.5	2.2	70.6	2.0	92.3
Washington, DC	17.5	2.2	78.3	1.6	99.6
Los Angeles	17.5	2.2	27.7	0.5	47.9
Phoenix	17.5	2.2	23.7	2.4	45.8
Albuquerque	17.5	2.2	80.6	1.2	101.5
Dallas	17.5	2.2	43.8	5.6	69.1
Tampa	17.5	2.2	9.2	3.2	32.1
Atlanta	17.5	2.2	54.9	1.5	76.1
Miami	<u>17.5</u>	<u>2.2</u>	<u>2.9</u>	<u>3.2</u>	<u>25.8</u>
Averages:	17.5	2.2	81.3	1.6	102.6

Note: Building module used was 20' x 40' x 14', with a winter inside design temperature of 68°F; a summer inside design temperature of 75°F; and a ventilation rate of 6 changes per hour (16).

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SECTION 5

SYSTEMS COST ESTIMATES

This section presents cost data for several example granular activated carbon systems which illustrate application of this technology to drinking water, municipal wastewater, and industrial wastewater treatment. The methodology and underlying assumptions used in combining the modular costs into system costs are carefully explained.

Preparation of system costs involves three steps:

- design definition,
- combination of modular costs and operating requirements to develop system direct capital costs and processing expenses, and
- development of system direct capital costs and processing expenses into the total capital investment and total annual cost.

5.1 DESIGN DEFINITION

Actual system design requires the application of design principles discussed in Section 3 with finer points discussed elsewhere (1, 2, 3, 4, 5) combined with test data, or design model calculations and assumptions or data on the raw water being treated.

Design calculations determine the sizes of the various process modules comprising the total granular activated carbon system. The particular modules selected for any given estimate define the scope of the estimate. Specifications must also be established for each module once the size has been determined (e.g., type of adsorber). These design parameters are used to prepare the cost estimate.

5.2 SYSTEM COST DEVELOPMENT

Once the type, sizing, and specifications of equipment have been established, modular capital and operating cost data can be appropriately combined to obtain total system direct capital cost and processing expenses. Then, factors are applied and additional cost elements added as demonstrated in this section to arrive at the bottom line costs for total capital investment and total annual cost.

The formats for final system cost development were shown in Tables 2-1 and 2-2, respectively, for total capital investment and total annual cost. Cost elements that must be added to the modular cost total are discussed below.

5.2.1 Capital Cost Elements

The capital cost elements that must be added to direct capital costs include:

- engineering and supervision,
- construction field expenses,
- contractor fees,
- contingency,
- interest during construction,
- startup,
- land, and
- working capital.

Selection of values for each of these is discussed. Definitions are discussed elsewhere (6).

Engineering and Supervision

Engineering and supervision costs can vary with the size and the complexity of an individual project. In this report a fixed 10 percent of direct capital cost was used.

Construction Field Expenses

A fixed 5 percent of direct capital cost was used in this report.

Contractor Fees

Contractor fees can vary as a percentage of total bare module cost with the size of a project. In this report a fixed value of 10% was used.

Contingency

Contingency costs can reflect both the level of information from which the estimate was prepared, the state of technology development, and a judgment on the potential for unanticipated events to influence the cost of a project. A fixed value of 15% of total bare module cost is used in this report.

Interest During Construction

Interest during construction, accounted for by applying a factor to total bare module cost, reflects both the interest rate charged on the construction loan, the length of the construction period, and the mode of financing.

An annual interest rate of 12% was assumed for the construction loan. The mode of financing was assumed to be by direct borrowing of the total amount during an 18-month construction period. A borrowing schedule of one-third of the loan amount each six months during construction was also assumed (33%-33%-33% borrowing schedule).

Startup Costs

Startup costs are highly variable for individual projects and depend on both system design complexity, design and construction integrity, as well as training, skill, and commitment of the startup staff. In this report, startup costs are taken as 5% of total bare module cost.

Land

Land area required for systems was estimated from the area requirements for individual subsystems of the total GAC system. A land cost of \$5,000 per acre was assumed. Land costs are highly variable and the user should select an appropriate value for the location under consideration for the potential plant. estimating for. In general, however, land costs are likely to be a small percentage of total system costs for GAC.

Working Capital

Working capital for a granular activated carbon system covers materials inventories and disbursement obligations over a specified period of time. An amount equivalent to 60 days of processing expenses was assumed for capital investment estimates in this report. Uhl (6) points out that working capital can be computed in various other ways.

5.2.2 Total Annual Cost

Unit prices for calculating processing expenses are given in Table 5-1. Various cost elements are added to processing expenses to obtain total annual cost. The cost elements that must be added to processing expenses include:

- plant overhead,
- insurance and property taxes,
- depreciation,
- general expenses,

TABLE 5-1. UNIT PRICES USED FOR CALCULATING PROCESSING EXPENSES^a

Labor	\$11.00 per hour
Electricity	\$0.05 per kWh
Fuel	
Natural Gas	\$2.46 per thousand cubic feet
No. 2 Fuel Oil	\$0.98 per gallon
Granular Activated Carbon	\$0.75 per lb

^aThe value for labor is an approximation for skilled manufacturing labor for the base time period of September 1980. Electricity and fuel costs were obtained from Reference 10. The average or typical price for granular activated carbon is based on literature values and is an estimate for September 1980.

- return on equity, and
- income taxes.

Selection of values for each of these is discussed. The assignment of values to these items is an accounting procedure and, as such, can be expected to vary with different organizations either preparing or using cost estimates. Values used here are intended to be representative. Definitions are discussed elsewhere (6).

Plant Overhead

Fifty percent of labor costs is assumed for plant overhead. This is one of several values frequently used in preparing estimates (6).

Insurance and Property Taxes

A factor of 2 percent of total depreciable capital investment is used. Insurance and property taxes will depend strongly on locality for an actual plant.

Depreciation

Depreciation for GAC systems has been taken at a straight line rate with a system lifetime of 20 years for public projects (e.g. drinking water and municipal wastewater), and 15 years for private projects (e.g. industrial wastewater).

General Expenses

These expenses, sometimes also referred to as general and administrative expenses (G&A), comprise administrative expenses and average debt interest in this report. Administration was taken as 1 percent of total depreciable investment. Average debt interest was calculated directly using an interest rate of 12 percent and procedures discussed in Uhl (6). The average interest on debt is given by:

$$ADI = IR \times \frac{D}{V} \times \left[\left(1 + \frac{1}{N} \right) \left(\frac{TDI}{2} \right) + TCI - TDI \right]$$

where ADI = average debt interest

IR = annual interest rate

$\frac{D}{V}$ = debt fraction of total capitalization,

N = number of years for computing financial depreciation

TDI = total depreciable investment, and

TCI = total capital investment

For the drinking water and municipal wastewater examples in this report (public sector projects) $D/V = 1.0$. For the industrial wastewater example (private sector project) $D/V = 0.25$.

Return on Equity

There is no return on equity for public sector projects. For private sector projects an average return on equity is calculated analogously to average debt interest shown above. The after-tax return rate is substituted for annual interest rate, and the equity fraction of total capitalization for debt fraction in the preceding equation. For the industrial wastewater example in this report, the equity fraction, $C/V = 0.75$. A return rate of 15 percent was assumed.

Income Taxes

Income taxes are levied on the gross profit which is the after tax return on equity plus the amount for the income taxes. An income tax rate of 46 percent of gross profit was used.

5.3 EXAMPLE SYSTEMS

An example system was selected from each of the three general application areas of:

- drinking water,
- municipal wastewater, and
- industrial wastewater.

Design criteria for each example system are summarized in Table 5-2. Specific features of each system are discussed in detail in the individual system sections.

All three example systems have been selected at the same design capacity of 10 mgd to provide a clear illustration of how design parameters can influence system cost at the same design flow rate.

Differences in design features should be apparent from Table 5-2 and include:

- type of adsorbers,
- size of adsorbers due to differences in contact times and permissible hydraulic loadings,
- sizes of carbon storage and handling systems, and
- regeneration requirements.

TABLE 3-1. DESIGN CRITERIA AND COST ESTIMATING PREMISES FOR THREE EXAMPLE GAC SYSTEMS

Application Area:	Drinking Water	Municipal Wastewater ^a	Industrial Wastewater
Hypothetical Treatment Objectives:	TOC breakthrough limited to 0.5 mg/l	BOD removal to 10 mg/l	Phenol removal to 1.0 mg/l
Influent Characteristics:			
Flow rate for design (mgd)	10	10	10
Temperature (°F)	70	70	70
BOD ₅ (mg/l)	-	50	-
COD (mg/l)	-	-	200
TOC (mg/l)	2.5	-	-
Other (mg/l)	-	-	-
SS (mg/l)	500	500	phenol, 100
Adsorbent Parameters:			
Empty bed contact time (EBCT) (min.)	30	30	30
Hydraulic loading (gpm/ft ²)	6	4	4
Carbon type	8 x 30	8 x 30	8 x 30
Adsorbent type	fixed bed, series, pressure, downflow, parallel	fixed bed, pressure, downflow, parallel	pulsed bed upflow, parallel
Adsorbent volume (ft ³)	1697 per adsorbent vessel	1242 per adsorbent vessel	6786 per adsorbent
No. parallel adsorbent modules	10	16	16
No. individual adsorbent vessels	22	16	16
Regeneration Parameters:			
Carbon dosage (CD) (lb/10 ³ gal)	1,000	300	1,000
Regeneration frequency (days)	45	289	several times daily
Forcane rate ^b (lb/day)	9,910	3,097	10,000
Forcane loading:			
multibed ^c (lb/hr/ft ²)	-	50	-
fluid bed (lb/hr/ft ²)	-	-	1,440
Infrared	-	-	-
Energy usage:			
multibed ^c (Btu/lb C)	-	3,000	-
fluid bed (Btu/lb C)	3,500	-	-
Infrared (kW/lb C)	-	-	0.8
Steam usage (lb/lb C)	-	-	-
multibed ^c	-	1.0	-
fluid bed	1.0	-	-
Infrared	-	-	-
Process water ^d (gal/lb C)	1.0	1.0	1.0

^aOperating rate. Design rate = 1.5 x operating rate.
^bFor steam boiler makeup and wet scrubber particulate control in regeneration system.

In real systems, these kinds of differences result from differences in the influent water characteristics. For example, in comparing drinking water to municipal wastewater treatment, the contact times are identical, but the hydraulic loading differs. This might reflect differences in the particular contactor design selected or differences in suspended solids concentrations in the respective influent streams. The drinking water system is assumed to operate with a lower influent suspended solids concentration which permits a higher hydraulic loading. Carbon dosages differ, reflecting individual influent characteristics which are related to the chemical species present and to their adsorption properties.

The following individual sections present the cost estimates for each example. This is followed by an illustrative sensitivity analysis on one system in Section 5.7.

5.4 DRINKING WATER TREATMENT

The plant capacity of 10 mgd used for this system corresponds to a community population of 5,000 people, based on a daily per capita water design basis of 200 gallons. Figure 5-1 is a schematic of the system. Design parameters were given in Table 5-2.

Combining modular costs into total direct capital cost and processing expenses for the GAC system is illustrated in Tables 5-3 and 5-4, respectively. Details of developing the system costs are given in Appendix A. Total capital investment and total annual operating expenses are given in Tables 5-5 and 5-6, respectively.

These costs form the base case for the sensitivity analysis discussed in Section 5.7.

5.5 MUNICIPAL WASTEWATER TREATMENT

For municipal wastewater, a system capacity of 10 mgd corresponds to a population of 7,000 people based on a daily per capita water design basis of 160^a gallons. The municipal GAC system is assumed to treat a conventional secondary effluent which has been filtered through a granular media filter. Figure 5-2 is a schematic of the system. Design parameters were given in Table 5-2.

Combining modular costs into total direct capital cost and processing expenses for the GAC system is shown in Tables 5-7 and 5-8, respectively. Details of developing the system costs are given in Appendix B. Total capital investment and total annual operating expenses are given as Tables 5-9 and 5-10, respectively.

^aThe difference between the design basis for per capita water use for drinking water and wastewater systems reflects standard practice. See References for discussions of per capita use rates.

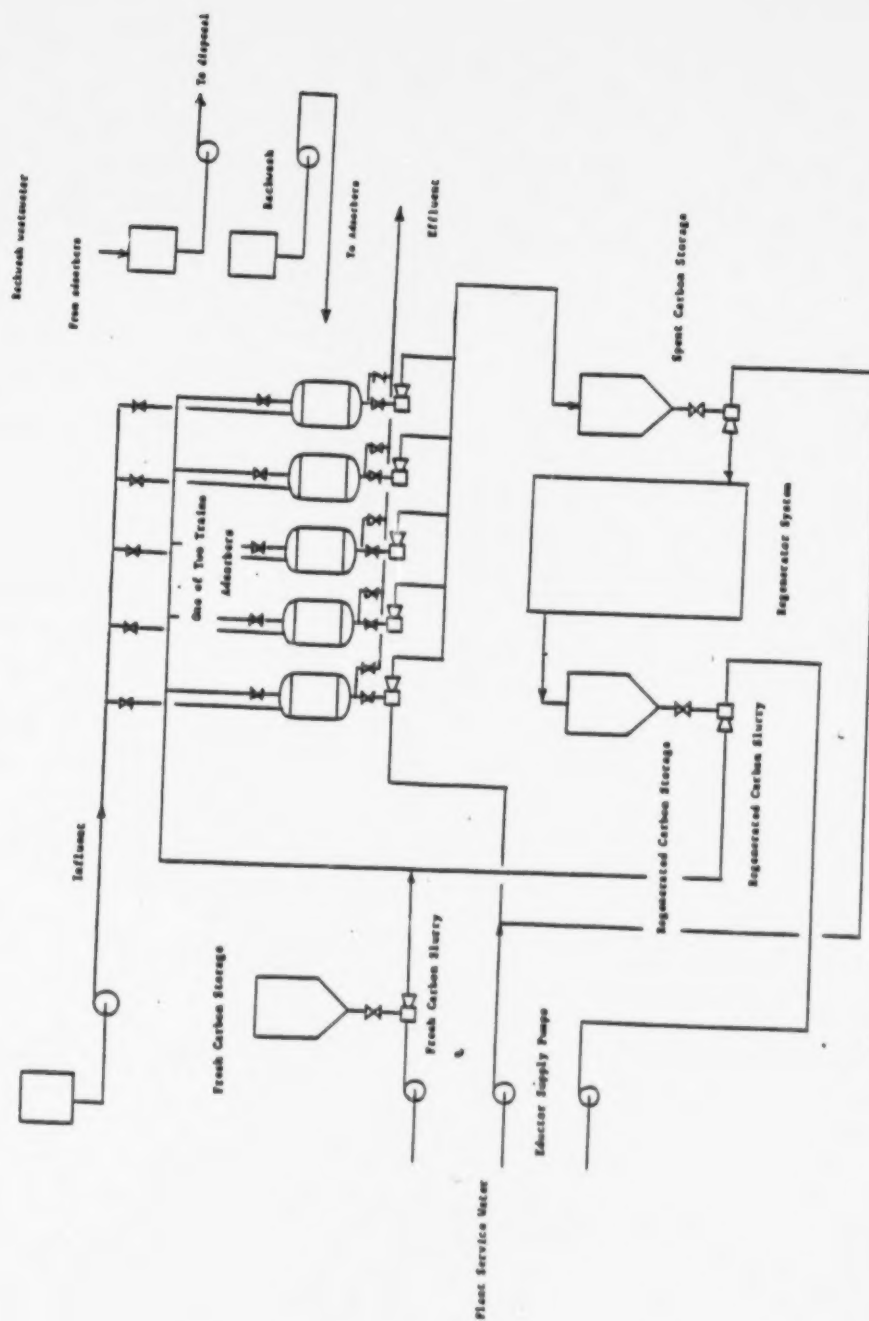


Figure 5-1. GAC system for drinking water treatment.

TABLE 5-3. DIRECT CAPITAL COST ESTIMATE FOR DRINKING
WATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: infrared
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

Cost (\$1000)

Battery Limits

Influent Pumping	200
Adsorbers	2,288
Initial Carbon Charge	672
Regeneration System	575
Fresh Carbon Storage and Transfer	60
Spent Carbon Storage and Transfer	68
Regenerated Carbon Storage and Transfer	68
Backwash System	64
Surface Wash System	--
Subtotal Battery Limits	3,995

Auxiliaries and Offsites

Buildings	650
Interconnecting and Offsite Piping	166
Electrical Supply and Distribution	50
Site Preparation	<u>15</u>
Subtotal Auxiliaries and Offsites	871
TOTAL DIRECT CAPITAL COST	4,876

TABLE 5-4. PROCESSING EXPENSE ESTIMATE FOR DRINKING
WATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: infrared
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>Cost (\$1000)</u>
<u>Battery Limits</u>	
Influent Pumping	90
Adsorbers	85
Regeneration System	380
Carbon Losses	136
Fresh Carbon Storage and Transfer	1
Spent Carbon Storage and Transfer	5
Regenerated Carbon Storage and Transfer	5
Backwash System	<u>5</u>
Subtotal Battery Limits	707
<u>Auxiliaries and Offsites</u>	
Buildings	132
Interconnecting and Offsite Piping	2
Electrical Supply and Distribution	<u>1</u>
Subtotal Auxiliaries and Offsites	135
	=====
TOTAL PROCESSING EXPENSES	842

TABLE 5-5. TOTAL CAPITAL INVESTMENT FOR DRINKING WATER TREATMENT
GAC SYSTEM EXAMPLE

Flow: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: infrared
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>(\$1000)</u>
Direct cost items (see Table 5-3)	
TOTAL DIRECT COST (from Table 5-3)	4,876
Indirect cost items	
Engineering and supervision (10%)	488
Field construction expenses (5%)	<u>244</u>
TOTAL BARE MODULE COST	5,608
Contingency (15%)	841
Contractor fee (10%)	<u>561</u>
TOTAL PLANT COST	7,010
Interest during construction ^a (12%)	841
Startup (5%)	<u>421</u>
TOTAL DEPRECIABLE INVESTMENT	8,272
Land (16,200 ft ² , \$5,000 per acre)	2
Working capital (60 days processing expenses)	<u>108</u>
TOTAL CAPITAL INVESTMENT	8,382

^aBased on a 12% annual rate of interest, a construction period of 18 months, and a 33%-33%-33% borrowing schedule.

TABLE 5-6. TOTAL ANNUAL COST FOR DRINKING WATER TREATMENT GAC SYSTEM EXAMPLE

Flow: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: infrared
CD: 1000 lb/10 ⁶ day	Cost base year: September, 1980

	(\$1000)
Labor	102
Maintenance materials	51
Power (Electricity)	398
Fuel	—
Carbon losses	136
Other (includes building maintenance and lesser process expenses)	<u>153</u>
PROCESSING EXPENSES	840
Overhead (50% of labor)	51
Insurance and property taxes (1% of TPC) ^a	70
Depreciation (5% of TDI) ^{b,c}	<u>413</u>
TOTAL OPERATING COSTS	1,374
General expenses ^d	<u>618</u>
TOTAL ANNUAL OPERATING EXPENSES	1,992
Return on equity	both zero for public projects
Income taxes	
	<u>-0-</u>
TOTAL ANNUAL COST	1,992

^aTPC = total plant cost

^bTDI = total depreciable investment.

^cStraight line depreciation over 20 years.

^dIncludes administration at 1 percent of total depreciable investment (see Reference 6, p.14 and p. J-14), and average interest on debt (see Reference 6, p.J-14). Average interest on debt for an annual interest rate of 12 percent is:

$$.12 \times \frac{D}{V} \times \left[\left(1 + \frac{1}{n_{DF}} \right) \left(\frac{TDI}{2} \right) + TCI - TDI \right]$$

where $\frac{D}{V}$ = the percentage of capital financed by debt.

n_{DF} = number of years for computing financial depreciation.

TCI = total capital investment.

TABLE 5-7. DIRECT CAPITAL COST ESTIMATE FOR MUNICIPAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: multihearth furnace
CD: 300 lb/10 ⁶ gal	Cost base year: September, 1980

Cost (\$1000)

Battery Limits

Influent Pumping	200
Adsorbers	1,840
Initial Carbon Charge	652
Regeneration System	810
Fresh Carbon Storage and Transfer	60
Spent Carbon Storage and Transfer	80
Regenerated Carbon Storage and Transfer	80
Backwash System	64
Surface Wash System	—
Subtotal Battery Limits	3,786

Auxiliaries and Offsites

Buildings	190
Interconnecting and Offsite Piping ^a	166
Electrical Supply and Distribution	28
Site Preparation	13
Subtotal Auxiliaries and Offsite	4,183
	=====
TOTAL DIRECT CAPITAL COST	4,263

^aDetermined on a site-specific basis from layout plan, line sizing from flow rate, and unit piping and valve costs from Tables 4-1 and 4-2.

TABLE 5-8. PROCESSING EXPENSE ESTIMATE FOR MUNICIPAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: multihearth
CD: 300 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>Cost (\$1000)</u>
<u>Battery Limits</u>	
Influent Pumping	90
Adsorbers	70
Regeneration System	90
Carbon Losses	41
Fresh Carbon Storage and Transfer	1
Spent Carbon Storage and Transfer	3
Regenerated Carbon Storage and Transfer	3
Backwash System	<u>2</u>
Subtotal Battery Limits	307
<u>Auxiliaries and Offsites</u>	
Buildings	56
Interconnecting and Offsite Piping ^a	2
Electrical Supply and Distribution	<u>1</u>
Subtotal Auxiliaries and Offsite	59
TOTAL PROCESSING EXPENSES	<u>366</u>

^aDetermined on a site-specific basis from alyout plan, line sizing from flow rate, and unit piping and valve costs from Tables 4-1 and 4-2.

TABLE 5-9. TOTAL CAPITAL INVESTMENT FOR MUNICIPAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow: 50 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 30 min.	Regeneration type: multihearth furnace
CD: 300 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>Cost (\$1000)</u>
Direct cost items (see Table 5-7)	
TOTAL DIRECT COST (from Table 5-7)	4,183
Indirect cost items	
Engineering and supervision (10%)	418
Field construction expenses (5%)	<u>209</u>
TOTAL BARE MODULE COST	4,810
Contingency (15%)	722
Contractor fee (10%)	<u>481</u>
TOTAL PLANT COST	6,013
Interest during construction ^a (12%)	722
Startup (5%)	<u>301</u>
TOTAL DEPRECIABLE INVESTMENT	7,036
Land (14,000 ft ² \$5,000 per acre)	2
Working capital (60 days processing expenses)	<u>60</u>
TOTAL CAPITAL INVESTMENT	7,098

^aBased on a 12% annual rate of interest, a construction period of 18 months, and a 33%-33%-33% borrowing schedule.

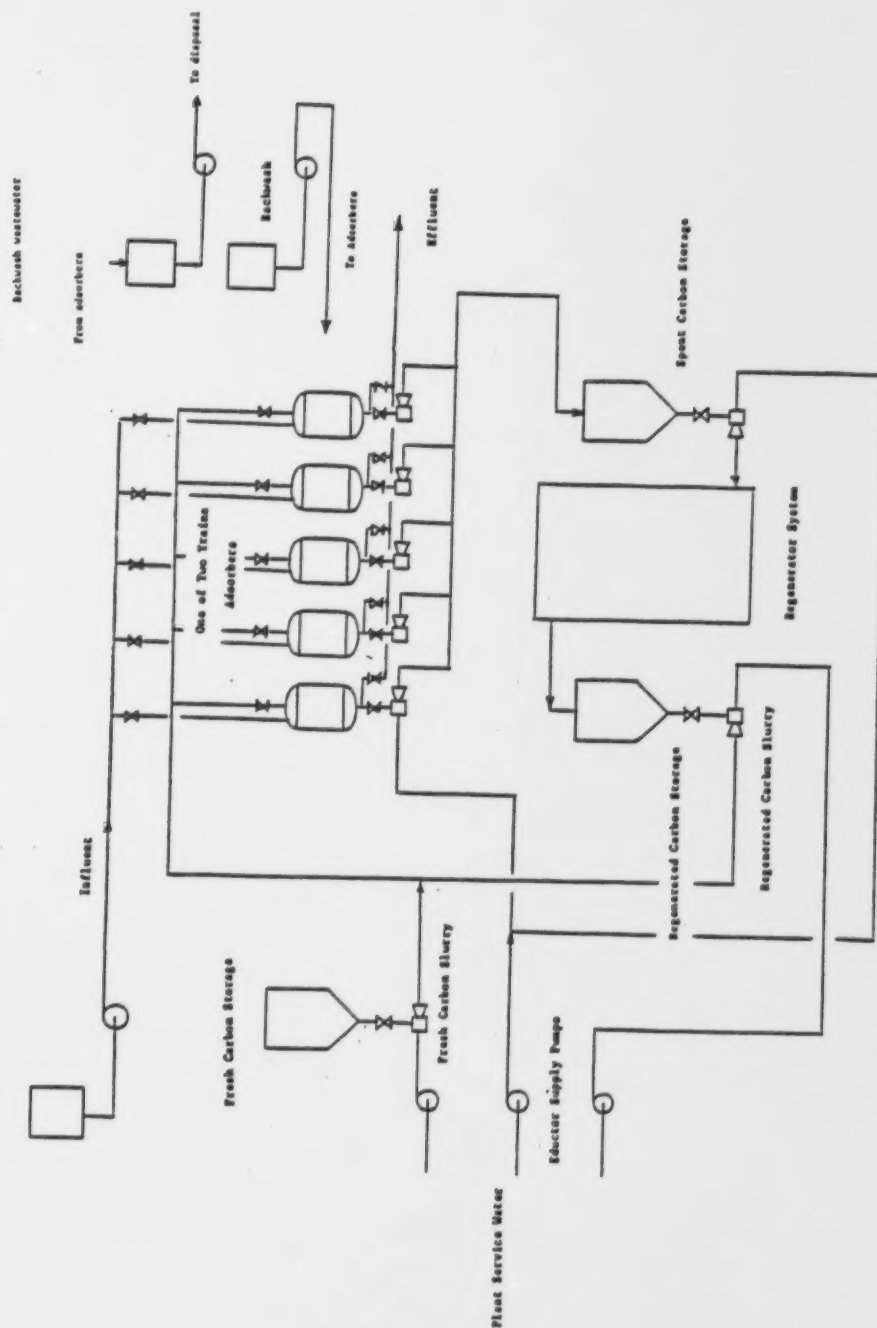


Figure 5-2. GAC system for municipal wastewater treatment.

TABLE 5-10. TOTAL ANNUAL COST FOR MUNICIPAL WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow:	10 mgd	Adsorber type:	fixed-bed, pressure steel, downflow
EBCT:	30 min.	Regeneration type:	multihearth furnace
CD:	300 lb/10 ⁶ gal	Cost base year:	September, 1980.

			<u>(\$1000)</u>
Labor			77
Maintenance materials			44
Power (Electricity)			92
Fuel			37
Carbon losses			41
Other (includes building maintenance and lesser process expenses)			<u>75</u>
PROCESSING EXPENSES			366
Overhead (50% of labor)			38
Insurance and property taxes (1% of TPC) ^a			60
Depreciation (5% of TDI) ^{b,c}			<u>351</u>
TOTAL OPERATING COSTS			815
General expenses (2% of TDI) ^d			<u>520</u>
TOTAL ANNUAL OPERATING EXPENSES			1,335
Return on equity	both zero for publically		
Income taxes	owned facilities		<u>-0-</u>
TOTAL ANNUAL COST			1,335

^aTPC = total plant cost

^bTDI = total depreciable investment.

^cStraight line depreciation over 20 years.

^dIncludes administration at 1 percent of total depreciable investment (see Reference 6, p.14 and p. J-14), and average interest on debt (see Reference 6, p.J-14). Average interest on debt for an annual interest rate of 12 percent is:

$$.12 \times \frac{D}{V} \times \left[\left(1 + \frac{1}{n_{DF}} \right) \left(\frac{TDI}{2} \right) + TCI - TDI \right]$$

where $\frac{D}{V}$ = the percentage of capital financed by debt.

n_{DF} = number of years for computing financial depreciation.

TCI = total capital investment.

5.6 INDUSTRIAL WASTEWATER TREATMENT

The wide variety of characteristics found with industrial wastewaters precludes characterizing a "typical" GAC system for this application. Overall design concepts are, however, the same as for drinking water and wastewater applications. As shown in the design parameters of Table 5-2, an upflow pulsed bed was selected for this example. Also, a longer contact time of 60 minutes was selected for this case rather than the 30 minutes used for drinking water or municipal wastewater. This reflects experience with some industrial wastewater GAC systems which have required longer contact times than has usually been the case with drinking water or municipal wastewater treatment. Figure 5-3 illustrates the system.

Combining modular costs into system costs for direct capital and processing expenses are shown as Tables 5-11 and 5-12, respectively. Details of the development of these costs are given in Appendix C. Total capital investment and total annual operating expenses are given in Tables 5-13 and 5-14, respectively.

5.7 COST SENSITIVITY ANALYSIS

The three examples just presented illustrate the many factors that influence costs of GAC systems. The sensitivity of GAC system costs to changes in the values of these factors can be examined by a sensitivity analysis. A sensitivity analysis is useful in evaluating relationships between influent characteristics, performance requirements, system design, and system costs for specific applications. Two previous sensitivity studies on GAC systems are found in References 7 and 8. The present report provides the tools to expand on these earlier studies by providing additional cost data and perspectives to permit more detailed analysis. Although presentation of an exhaustive sensitivity analysis on GAC systems is beyond the scope of this report, an example analysis is provided. Using the drinking water system example as a base case, the influence of several variables on direct capital cost (and, therefore, depreciable investment which is obtained from direct cost by applying factors), processing expenses, and total annual cost is examined.

A sensitivity analysis can be conducted by changing a given variable while holding all others constant, or by changing a given variable and also accounting for interactions with other variables which cause their values to change simultaneously. In our example, each variable was examined individually while others were held constant.

Results of sensitivities for total depreciable investment, processing expenses, and total annual cost are illustrated in Figures 5-4, 5-5, and 5-6 respectively.

The first variable examined for sensitivity effects on capital costs and processing expenses was contact time. At a given flow rate and hydraulic loading, contact time determines carbon bed volume, and hence adsorber vessel volume. Shorter contact times result in less adsorber volume and lower costs

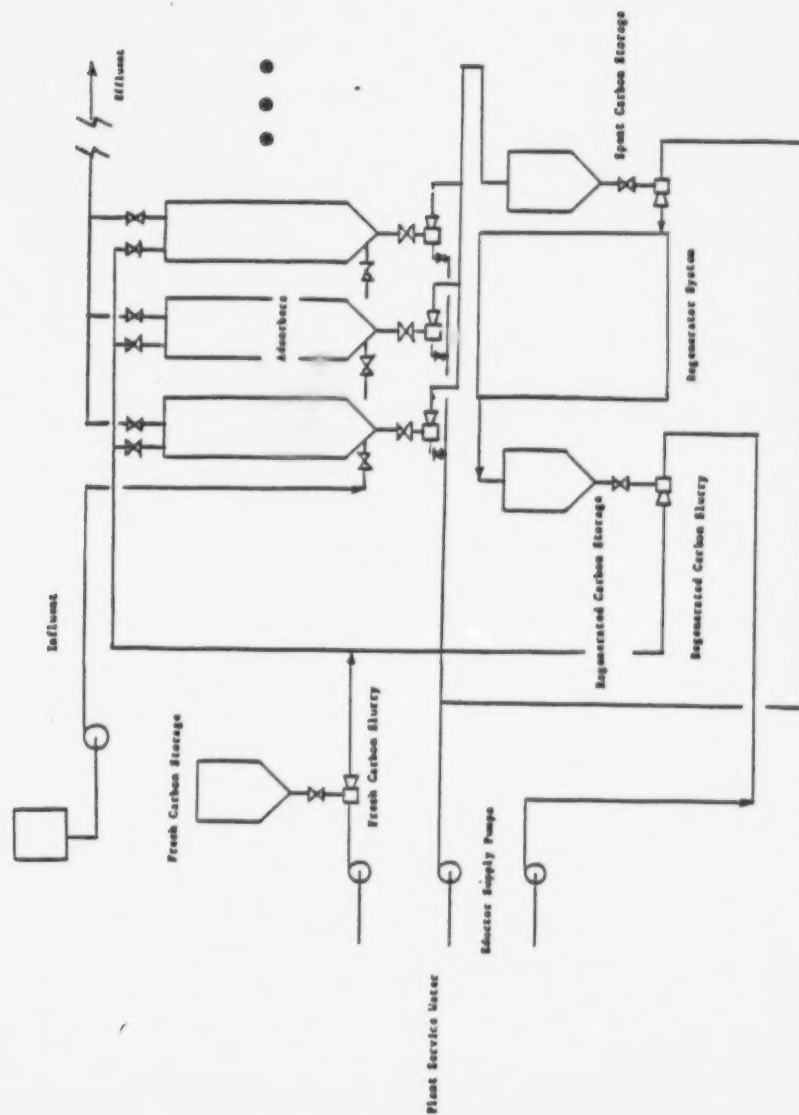


Figure 5-3. GAC system for industrial wastewater treatment.

TABLE 5-11. DIRECT CAPITAL COST ESTIMATE FOR INDUSTRIAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: pulsed bed
EBCT: 60 min.	Regeneration type: fluid-bed
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>Cost (\$1000)</u>
<u>Battery Limits</u>	
Influent Pumping	
Adsorbers	200
Initial Carbon Charge	3,680
Regeneration System	1,954
Fresh Carbon Storage and Transfer	1,100
Spent Carbon Storage and Transfer	60
Regenerated Carbon Storage and Transfer	30
Backwash System	30
Surface Wash System	—
Subtotal Battery Limits	7,054
<u>Auxiliaries and Offsites</u>	
Buildings	
Interconnecting and Offsite Piping ^a	150
Electrical Supply and Distribution	123
Site Preparation	25
	<u>13</u>
Subtotal Auxiliaries and Offsites	311
TOTAL DIRECT CAPITAL COST	<u>7,365</u>

^aDetermined on a site-specific basis from layout plan, line sizing from flow rate, and unit piping and valve costs from Tables 4-1 and 4-2.

TABLE 5-12. PROCESSING EXPENSE ESTIMATE FOR INDUSTRIAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow rate: 10 mgd	Adsorber type: pulsed bed
EBCT: 60 min.	Regeneration type: fluid-bed
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

	<u>Cost (\$1000)</u>
<u>Battery Limits</u>	
Influent Pumping	90
Adsorbers	70
Regeneration System	105
Carbon Losses	137
Fresh Carbon Storage and Transfer	1
Spent Carbon Storage and Transfer	3
Regenerated Carbon Storage and Transfer	3
Backwash System	--
Subtotal Battery Limits	409
<u>Auxiliaries and Offsites</u>	
Buildings	46
Interconnecting and Offsite Piping ^a	1
Electrical Supply and Distribution	--
Subtotal Auxiliaries and Offsite	47
	=====
TOTAL PROCESSING EXPENSES	456

^aDetermined on a site-specific basis from layout plan, line sizing from flow rate, and unit piping and valve costs from Tables 4-1 and 4-2.

TABLE 5-13. TOTAL CAPITAL INVESTMENT FOR INDUSTRIAL
WASTEWATER TREATMENT GAC SYSTEM EXAMPLE

Flow: 10 mgd	Adsorber type: pulsed bed
EBCT: 60 min.	Regeneration type: fluid-bed
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980

	(\$1000)
Direct cost items (see Table 5-11)	
TOTAL DIRECT COST (from Table 5-11)	7,365
Indirect cost items	
Engineering and supervision (10%)	736
Field construction expenses (5%)	<u>368</u>
TOTAL BARE MODULE COST	8,469
Contingency (15%)	1,270
Contractor fee (10%)	<u>847</u>
TOTAL PLANT COST	10,586
Interest during construction ^a (12%)	1,270
Modifications and startup (5%)	<u>529</u>
TOTAL DEPRECIABLE INVESTMENT	12,385
Land (13,000 ft ² \$5,000 per acre)	2
Working capital (60 days processing expenses)	<u>72</u>
TOTAL CAPITAL INVESTMENT	12,459

^aBased on a 12% annual rate of interest, a construction period of 18 months, and a 33%-33%-33% borrowing schedule.

TABLE 5-14. TOTAL ANNUAL COST FOR INDUSTRIAL WASTEWATER TREATMENT
GAC SYSTEM EXAMPLE

Flow: 10 mgd	Adsorber type: pulsed bed
EBCT: 60 min.	Regeneration type: fluid-bed
CD: 1000 lb/10 ⁶ gal	Cost base year: September, 1980
	<u>(\$1000)</u>
Labor	85
Maintenance	50
Power (Electricity)	89
Fuel	45
Carbon losses	137
Other (includes building maintenance and lesser process expenses)	<u>49</u>
PROCESSING EXPENSES	455
Overhead (50% of labor)	42
Insurance and property taxes (1% of TPC) ^a	106
Depreciation (7% of TDI) ^{b,c}	<u>867</u>
TOTAL OPERATING COSTS	1,470
General expenses ^d (2.6% of TDI)	<u>324</u>
TOTAL ANNUAL OPERATING EXPENSES	1,794
Return on equity (6% of TDI)	754
Income taxes (46% of [TAC less TAOE])	<u>641</u>
TOTAL ANNUAL COST	3,189

^aTPC = total plant cost

^bTDI = total depreciable investment.

^cStraightline depreciation, 15 years.

^dIncludes administration at 1 percent of total depreciable investment (see Reference 6, p.14 and p. J-14), and average interest on debt (see Reference 6, p.J-14). Average interest on debt for an annual interest rate of 12 percent is:

$$.12 \times \frac{D}{V} \times \left[\left(1 + \frac{1}{n_{DF}} \right) \left(\frac{TDI}{2} \right) + TCI - TDI \right]$$

where $\frac{D}{V}$ = the percentage of capital financed by debt.

n_{DF} = number of years for computing financial depreciation.

TCI = total capital investment.

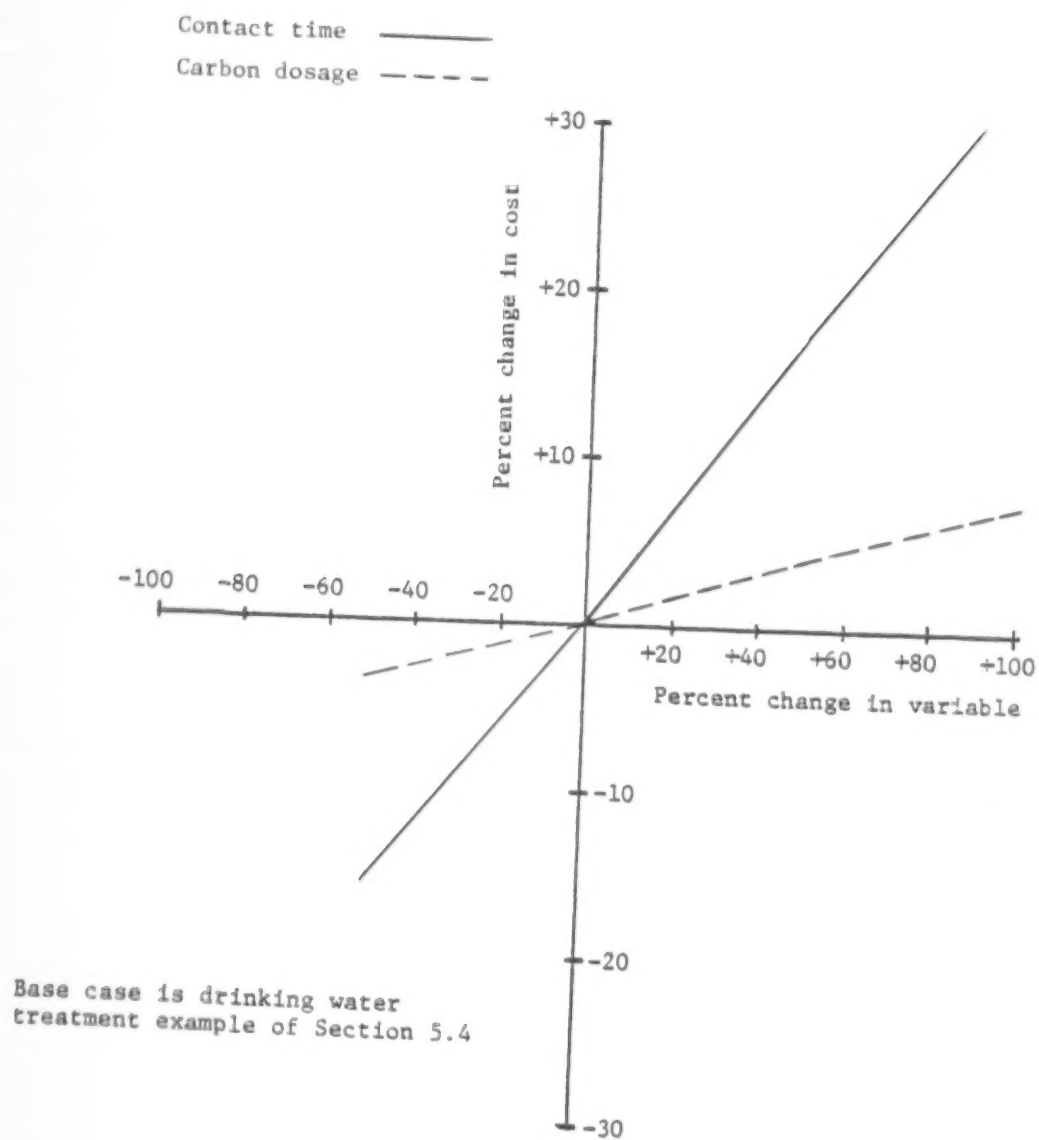


Figure 5-4. Total depreciable investment cost sensitivity example.

Power	_____
Carbon losses	_____
Labor	_____
Maintenance materials	_____

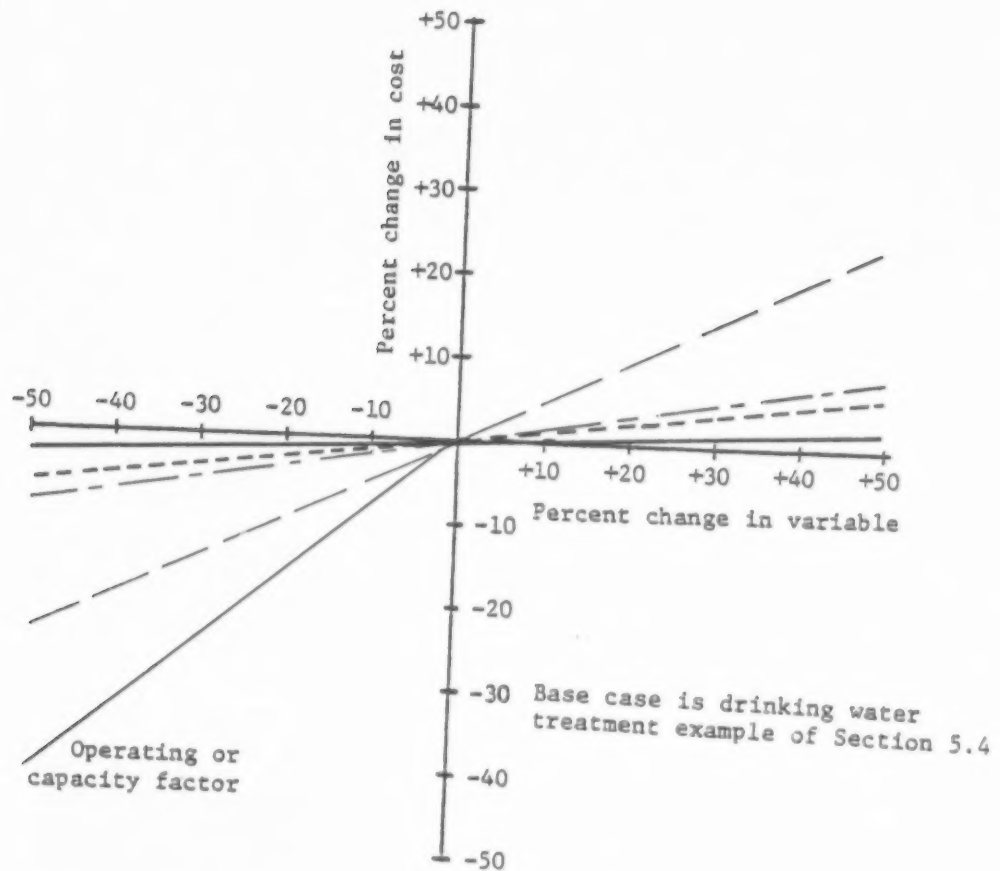


Figure 5-5. Processing expenses cost sensitivity example.

Total depreciable investment	_____
Processing expenses	
Interest costs	----
Carbon losses	-.-.-

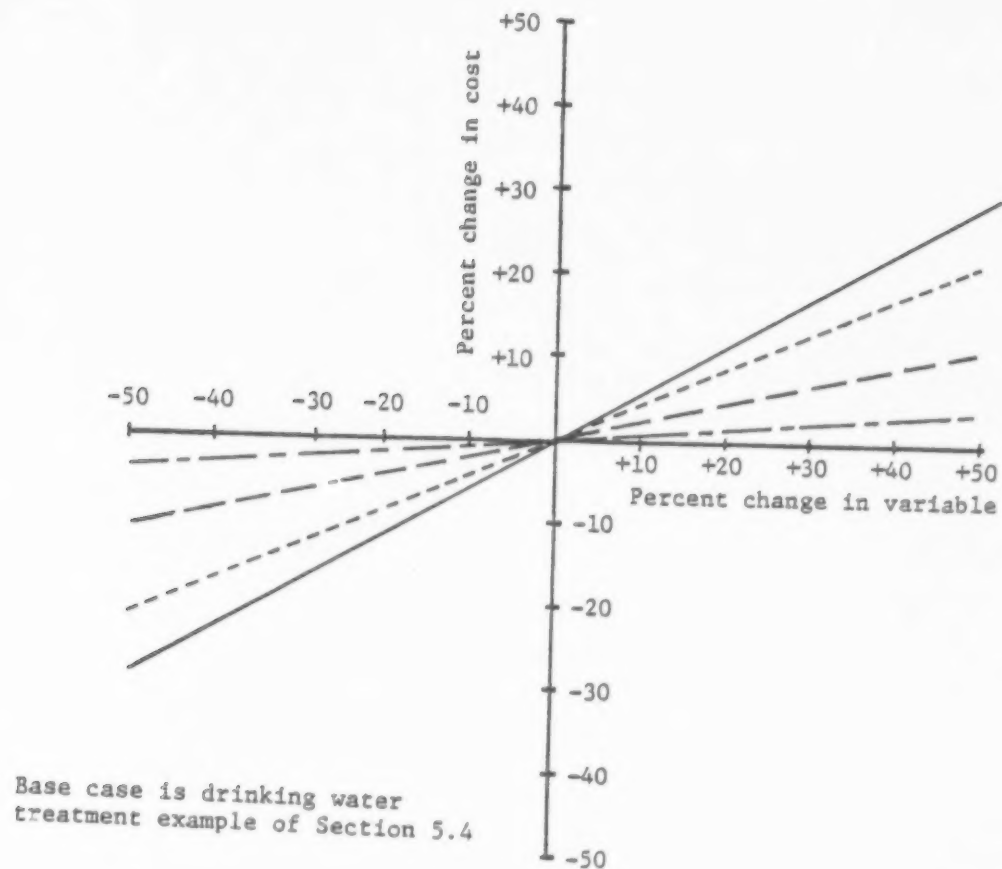


Figure 5-6. Total annual cost sensitivity example.

for adsorbers; longer contact times result in greater adsorber volume and increased costs for adsorbers. The sensitivity to contact time examined here is a simplification. There is an interaction between contact time and carbon dosage which has been neglected. This interaction results in a change in regeneration rate in addition to changes in adsorber volume when contact time is changed. The net result of this effect is, however, to reduce the cost sensitivity to contact time so that the simplification results in a more conservative estimate of the sensitivity.

The next variable examined was carbon dosage. Carbon dosage depends on the adsorption properties of individual influent streams (and the specific brand and grade of activated carbon used). Carbon dosage is expressed as pounds of carbon required per million gallons of water treated. The primary effect of changes in this variable is to alter regeneration frequency and hence regeneration rate. Cost changes are directly proportional to changes in carbon dosage.

Evaluating effects of cost changes for contact time and carbon dosage requires using the cost curves for adsorbers and regeneration systems since the primary variables related to cost are adsorber volume for contact time and regeneration rate for carbon dosage, rather than the contact time and regeneration rate themselves. Other sensitivities, however, are computed directly from the cost profiles shown previously in the pie charts of Figures 2-3, 2-4, and 2-5; and the assumed change in the particular cost component of interest. For example, a 50 percent change in the cost of buildings, 16 percent of direct capital costs in the base case, would yield: $0.50 \times 0.16 \times 100 = 8$ percent, the change in direct capital cost.

Cost sensitivities can also be determined for processing expenses and total annual cost.

In evaluating processing expenses and total annual cost, an important consideration is the capacity factor for equipment operating full time, or the operating factor for equipment operating at full capacity part of the time. In this report processing expenses and total annual cost are based on equipment operating at full system capacity, 24 hours per day, 365 days per year. Actual systems operate at lower rates with resultant changes in costs. Thus operating factor was chosen as a sensitivity variable. Certain components of processing expenses, such as electricity, change proportionally with the operating factor, while others such as labor may remain constant or change disproportionately. Capital charge components of total annual cost do not change.

Other sensitivity variables include labor, maintenance materials, electricity (power) and carbon losses for processing expenses, and processing expenses, interest cost, and carbon losses for total annual cost.

These sensitivity cases are just examples that illustrate an approach that can be used in applying this report to analyzing costs of GAC systems.

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APPENDIX A

CALCULATIONS FOR DRINKING WATER TREATMENT SYSTEM

APPENDIX A

CALCULATIONS FOR DRINKING WATER TREATMENT SYSTEM EXAMPLE AT 10 MGD

Adsorbers

Empty bed contact time = 30 min.

Hydraulic loading = 6 gpm/ft²

Total bed depth required:

$$\frac{6 \text{ gpm/ft}^2 \times 30 \text{ min.}}{7.5 \text{ gal/ft}^3} = 24 \text{ ft}$$

Assume a configuration of two adsorbers in series. In a series adsorber module each adsorber will contain one-half the total bed depth, or 12 ft. of carbon.

The total adsorber cross-sectional area can be found from the hydraulic loading and the feed rate to the treatment system. For a total flow rate of 10 mgd and a hydraulic loading of 6 gpm/ft², the total adsorber cross-sectional area is:

$$\begin{aligned} \text{Total cross-sectional area} &= \frac{(10 \times 10^6 \text{ gal/day}) \times (1 \text{ day}/1440 \text{ min})}{6 \text{ gal/min ft}^2} \\ &= 1157 \text{ ft}^2 \end{aligned}$$

The number of individual parallel adsorber modules can be found from the total cross-sectional area. For this example, a 12 ft. diameter adsorber vessel will be used. This is a standard size and is about the largest diameter vessel which can be easily transported to the erection site. Of course, other size vessels could be used; however, this would merely increase or decrease the number of adsorbers required and would not alter the calculation method shown here.

$$\text{Area of one adsorber} = \frac{\pi D^2}{4} = \frac{(12 \text{ ft})^2 \pi}{4} = 113 \text{ ft}^2$$

$$\text{Number of adsorber modules} = \frac{1157 \text{ ft}^2}{113 \text{ ft}^2} = 10.2$$

$$\text{Next larger whole number} = 11$$

Since there are 2 adsorbers per module, 22 vessels will be required.

The volume of activated carbon in each adsorber is:

$$\text{Volume activated carbon} = 113 \text{ ft}^3 \times 12 \text{ ft} = 1357 \text{ ft}^3 \text{ per adsorber}$$

Assuming an adsorber freeboard volume of 20 percent, the volume of the adsorber vessel is:

$$\text{Volume of one adsorber} = \frac{1357 \text{ ft}^3}{.80} = 1697 \text{ ft}^3$$

This corresponds to an adsorber height of 15 ft.

Refer to Figure 4-14. Select the 12 ft. diameter carbon steel adsorber with backwash. The direct capital cost for one adsorber = 104 K\$. For two adsorbers in series the cost = $2 \times 104 \text{ K\$} = 208 \text{ K\$}$. Total Adsorber area is: $22 \times 113 \text{ ft}^2 = 2486 \text{ ft}^2$. Processing expenses from Figure 4-15 = 85 K\$/yr.

For 11 adsorber modules, the direct capital cost is:

$$11 \times 208 \text{ K\$} = 2288 \text{ K\$}$$

$$\text{Initial carbon charge required} = 22 \times 1357 \text{ ft}^3 \times 30 \text{ lb/ft}^3 = 895,620 \text{ lb.}$$

$$\text{Direct capital cost} = \$0.75 \times 895,620 = 672 \text{ K\$}.$$

Backwash

It is assumed that backwash occurs sequentially throughout the system in only one adsorber vessel (not module of two vessels) at a time. The backwash system is therefore sized for only one adsorber vessel. Direct capital cost depends only on the individual adsorber. But, processing expenses for a GAC backwash system depend on how many vessels are in the system.

The adsorber area for a 12 ft diameter vessel is 113 ft².

The direct capital cost from Figure 4-22 for a backwash system with storage = 64 K\$.

Processing expenses from Figure 4-23 for 22 adsorber vessels (11 modules with 2 vessels each) = 5.4 K\$/yr.

Surface Wash

Surface wash is not used in this example.

Regeneration System

For adsorbers in parallel, startup is staggered so that all adsorbers do not require simultaneous discharge of spent carbon for regeneration. The scheduling of this startup can be made to correspond to the schedule for successive regeneration of each parallel adsorber which is calculated below.

In a series - parallel arrangement, the carbon in the lead adsorbers exhausts first. The second adsorbers in series then become the lead adsorbers. The train of lead adsorbers can be treated separately from the train of second adsorbers for calculating regeneration requirements.

The carbon exhaustion rate in the lead adsorbers can be calculated using a carbon dosage of 1000 lb/10⁶ gal of treated water. For each lead adsorber, the carbon exhaustion rate is:

$$\frac{1000 \text{ lb} \times 10 \times 10^6 \text{ gal}}{10^6 \text{ gal} \times \text{day}} = 909 \text{ lb/day per lead adsorber}$$

11 lead adsorbers

The carbon weight in each adsorber is:

$$1357 \text{ ft}^3 \times \frac{30 \text{ lb}}{\text{ft}^3} = 40,710 \text{ lb}$$

Each lead adsorber must therefore be regenerated:

$$\frac{40,710 \text{ lb per adsorber}}{909 \text{ lb/day}} = 45 \text{ days}$$

Each train of the two train, series - parallel system requires regeneration every 45 days as it completes duty as the lead train.

The first spent carbon is discharged from the first adsorber after 45 days of operation. Spent carbon is transferred to the spent carbon storage tank. The minimum storage capacity of this tank is chosen as 50% greater than adsorber volume. This volume, and the discharge interval between individual adsorbers determines the minimum regeneration rate required. The maximum discharge interval is calculated from the regeneration frequency and the number of parallel adsorber modules:

$$\text{Maximum discharge interval} = 45 \text{ days/11 adsorber modules} = 4.1 \text{ days per adsorber module}$$

The maximum discharge interval results in the minimum regeneration rate. The minimum regeneration rate is:

$$\frac{40,710 \text{ lbs}}{4.1 \text{ days}} = 9,930 \text{ lb/day}$$

If the regenerator is sized for 50 percent over the minimum regeneration rate, the design carbon throughput is:

$$9,930 \text{ lb/day} \times 1.5 = 14,900 \text{ lb/day.}$$

The direct capital cost for infrared regeneration from Figure 4-34 = 575 K\$. Processing expenses from Figure 4-35 for actual operation at 9,930 lb/day = 380 K\$/yr.

Fresh Carbon Storage and Transfer

Every 45 days, the total carbon regenerated in the lead train is:

$$40,710 \text{ lb per adsorber} \times 11 \text{ adsorbers} = 447,810 \text{ lb.}$$

If carbon losses in this case are 5 percent then losses are:

$$.05 \times 447,810 \text{ lb.} = 22,390 \text{ lb. per regeneration}$$

This amount must be replaced to the total carbon inventory at least every 45 days. The frequency of deliveries by a standard 40,000 lb truck is:

$$\frac{40,000 \text{ lb per delivery}}{22,390 \text{ lb/45 days}} = 80 \text{ days per delivery}$$

Assume a storage capacity equivalent to one standard truckload with 50 percent excess capacity. The storage volume is:

$$1.5 \times \frac{40,000 \text{ lb}}{30 \text{ lb/ft}^3} = 2000 \text{ ft}^3$$

The direct capital cost for carbon steel fresh carbon storage and transfer equipment from Figure 4-2 = 60 K\$. Processing expenses depend on how much carbon is transferred. At a regeneration operating rate of 9,930 lb/day and 5 percent losses, the average fresh carbon requirement is 497 lb/day. Processing expenses from Figure 4-3 = 1.4 K\$/yr.

Spent Carbon Storage and Transfer

Assume that the spent carbon storage volume is 50 percent greater than one adsorber volume. The spent carbon storage volume is then 2500 ft³.

The direct capital cost for carbon steel spent carbon storage and transfer equipment from Figure 4-2 = 68 K\$. As with fresh carbon storage and transfer, processing expenses depend on how much carbon is transferred. This quantity corresponds to the average regeneration rate of 9,930 lb/day. Processing expenses from Figure 4-3 = 5 K\$/yr.

Regenerated Carbon Storage and Transfer

Assume that the regenerated carbon storage volume is equal to the spent carbon storage volume.

The direct capital cost for regenerated carbon storage and transfer from Figure 4-2 = 68 K\$. Processing expenses on the same basis as for spent carbon storage from Figure 4-3 = 5 K\$/yr.

Influent Pumping

The system design flow rate is 10 mgd. Assume a head requirement of 80 ft.

The direct capital cost for influent pumping from Figure 4-37 = 200 K\$. Processing expenses from Figure 4-38 = 90 K\$/yr.

Buildings and Site Preparation

Costs for buildings and for site preparation in Section 4 were based on standard design concepts defined there. Use of these costs requires an estimate of the areas for each. The area for buildings depends on how much of the GAC system is housed, and what additional requirements there are for offices, laboratories, and other facilities. Site preparation costs depend on total area including unhoused portions of the site.

Area estimates for computing both building and site preparation costs are obtained from estimates of process area. Area requirements for various process modules were provided in Figures 4-40 through 4-46.

For this case, the results are:

<u>Process Module</u>	<u>Area (ft)²</u>
Influent pumping	2,700
Fresh carbon storage	500
Spent carbon storage	500
Regenerated carbon storage	500
Adsorbers	6,900
Backwash	660
Regeneration	<u>1,200</u>
Process area required	12,960

Other (assume at 25% of
process area

3,240

Total area required

16,200

This area is used to calculate costs for site preparation. From Figure 4-46, the direct capital cost = 15 K\$.

For the estimate of building costs, assume that the entire system is housed. The minimum required building area is the process area computed previously. Assume an additional 20 percent for offices, control room, laboratory, and other facilities. The total building area required is:

$$16,200 \text{ ft}^2 \times 1.2 = 19,440 \text{ ft}^2$$

From Figure 4-47, the direct capital cost = 650 K\$.

Building annual operating expenses include the costs of energy for lighting, heating, ventilating, air conditioning, and maintenance costs.

Energy costs depend on building area, geographical location, and energy prices. Table 4-7 lists energy requirements for a number of major metropolitan areas. Assuming a St. Louis, Mo., location for this example, the energy expenses for the building are:

$$16,200 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr} \times \$0.05/\text{kWh} = 112 \text{ K\$/yr}$$

Assume annual maintenance expenses at 3 percent of direct capital cost. Maintenance expenses are:

$$.03 \times 650 \text{ K\$} = 20 \text{ K\$/yr}$$

Building annual operating expenses = 132 K\$/yr.

Carbon Losses

Carbon losses might range from 5 to 15 percent of the carbon regenerated. In this case, 5 percent has been assumed.

$$\text{Carbon losses} = .05 \times 9930 \text{ lb/day} \times 365 \text{ day/yr} = 181,222 \text{ lb/yr}$$

$$\text{Processing expense for carbon losses} = \$0.75/\text{lb} \times 181,222 \text{ lb/yr} = 136 \text{ K\$/yr.}$$

Interconnecting and Off-site Piping

Pipe sizes, lengths of lines, and valving needs must be estimated. Pipe sizes can be obtained from the flow rate and corresponding line sizes listed in Table 4-5.

Influent and effluent lines:

$$\frac{10 \times 10^6 \text{ gal/day}}{1440 \text{ min/day}} = 6944 \text{ gpm}$$

The line size from Table 4-5 = 24 inches.

Carbon slurry lines:

Carbon slurry lines are based on a standard transfer rate of 70 gpm of slurry. The line size from Table 4-5 = 3 inches.

Backwash lines (in and out):

Backwash lines depend on the adsorber size and backwash rate. At 18 gpm/ft² for a 12 ft. diameter adsorber:

$$113 \text{ ft}^2 \times 18 \text{ gpm/ft}^2 = 2034 \text{ gpm.}$$

The line size from Table 4-5 = 14 inches

Surface wash lines:

None used in this example.

Service lines for compressed air and plant water:

Assume 2.0" lines for services to the process area.

The lengths of these lines depends on individual plant layout and spacing of units to be interconnected. Once lengths have been established costs for piping are obtained from Table 4-1. For each individual installation the number of valves must also be specified. Here it is assumed that two valves are required in each line. Costs for valves are obtained from Table 4-2.

A summary for interconnecting and off-site piping is given below:

<u>Line</u>	<u>Size(in)</u>	<u>Length(ft)</u>	<u>Direct Capital Cost (K\$)</u>	
			<u>Piping</u>	<u>Valves</u>
Influent	24	250	25	30
Effluent	24	250	25	30
Carbon slurry lines	3	250	2.3	3.1

Backwash in	14	250	12	9.4
Backwash out	14	250	12	9.4
Services	2	500	<u>6.0</u>	<u>1.8</u>

$$81.3 + 83.7 = 166 \text{ K\$}$$

Annual maintenance expenses at 1 percent per year = 1.7 K\$/yr.

Electrical Supply and Distribution

An estimate of the total installed electrical requirement is obtained by summing the major power requirement for power consuming modules. An allowance of 20 percent over this value is provided as a design contingency. Major system power requirements are for influent pumping, backwash pumping, carbon slurry transfers, regeneration, and building needs.

Power needs for each module are as follows:

Influent pumping:

Power is for pumping influent water to the adsorbers.

$$\text{Power} = 0.52 \times \text{flow rate in mgd} \times \text{pumping head in psig}$$

$$\text{In this case, Power} = 0.52 \times 10 \times 34 = 177 \text{ kW}$$

Carbon storage and transfer:

Power needs are for pumping carbon slurries during various transfer operations between the adsorbers and storage vessels. Power needs between carbon storage and regeneration are included under regeneration power requirements.

The power required for carbon slurry transfer depends on whether an eductor or direct pump system is used for transfer, with the slurry concentration, with the rate at which the slurry is pumped, and the pumping head. Power for the eductor is supplied to the motive water pump. In direct pump systems, power is supplied directly to the slurry pumps themselves.

In this report, the basis for slurry transfer power needs is a fixed transfer rate of 70 gpm of slurry.

For an eductor system, the motive water required is 5 times the process stream rate for a total of 350 gpm. The motive water must be supplied at a head pressure 60 psig above the eductor discharge pressure. For a discharge of 32 psig used in this example, the motive water supply pump head pressure is 92 psig.

Pumping Power = $.00075 \times \text{flow rate in gpm} \times \text{pumping head in psig}$.

Eductor power is therefore:

$$\text{Power} = .00075 \times 350 \times 92 = 24 \text{ kW}$$

For a direct pump system, the power at a discharge of 32 psig is :

$$\text{Power} = .00075 \times 70 \times 32 = 1.7 \text{ kW.}$$

Since it is unlikely that the intermittent carbon transfers between adsorbers and storage will occur simultaneously, the installed power requirements calculated above are sufficient, even though three separate types of storage are involved.

Backwash:

Power for the backwash system depends on the pumping rate and pumping head requirement. The pumping rate depends on individual adsorber area and the backwash flow rate per unit adsorber area. Pumping head depends on overall system design. In this report, backwash costs are based on a backwash flow rate per unit adsorber area of 18 gpm/ft² and an assumed pumping head requirement of 22 psig.

$$\text{Power} = .00075 \times 18 \times 22 \times \text{individual adsorber area in ft}^2.$$

In this case, the individual adsorber area is 113 ft².

$$\text{Power} = .00075 \times 18 \times 22 \times 113 = 34 \text{ kW}$$

Surface wash:

Considerations for the surface wash system are analogous to those for the backwash system, except that the pumping rate is lower and pumping head is higher to accommodate the higher head losses in a spray header system. In this report, the surface wash flow rate per unit adsorber area is 1.5 gpm/ft² with an assumed pumping head of 86 psig.

$$\text{Power} = .00075 \times 1.5 \times 86 \times \text{individual adsorber area in ft}^2.$$

In this example, no surface wash was used so that calculation of a power requirement is unnecessary.

Regeneration:

Power required for regeneration depends on regeneration rate and the type of regeneration system.

Requirements for the infrared systems considered in this report are:

$$\text{Infrared power} = 67 \times 10^{-3} \text{ kW/lb/day} \times 14,000 \text{ lb/day} = 938 \text{ kW}$$

Buildings:

The power required for buildings depends on size, location, and specific needs for heating, lighting, ventilation, and air conditioning. Average needs were given in Table 4-7.

In this case, the building area is 19,440 ft. A single-story building is specified. Assuming a St. Louis, MO location, the power requirement is:

$$\text{Power} = \frac{19,440 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr}}{8760 \text{ hr/yr}} = 308 \text{ kW}$$

Total Installed Power Requirement:

Adding the above and applying a factor of 1.2, the total is:

$$1481 \text{ kW} \times 1.2 = 1777 \text{ kW.}$$

The direct capital cost for an electrical substation and distribution system from Figure 4-39 = 50 K\$.

Annual maintenance expenses at 2 percent of direct capital cost = 1.0 K\$/yr.

APPENDIX B

CALCULATIONS FOR MUNICIPAL WASTEWATER TREATMENT SYSTEM

APPENDIX B

CALCULATIONS FOR MUNICIPAL WASTEWATER TREATMENT SYSTEM EXAMPLE AT 10 MGD

Adsorbers

Empty bed contact time: 30 min.

Hydraulic loading: 4 gpm/ft²

Total bed depth:

$$\frac{4 \text{ gpm/ft}^2 \times 30 \text{ min.}}{7.5 \text{ gal/ft}^3} = 16 \text{ ft}$$

For a single adsorber vessel in a fixed-bed, downflow adsorber module, the vessel is 20 ft. in height assuming a 20 percent freeboard volume.

The total adsorber cross-sectional area can be found from the hydraulic loading and the feedrate to the treatment system.

$$\begin{aligned} \text{Total cross-sectional area} &= 10 \times 10^6 \text{ gal/day} \times \frac{1 \text{ day}}{1440 \text{ min}} \\ &\quad \frac{4 \text{ gal/min ft}^2}{4 \text{ gal/min ft}^2} \\ &= 1736 \text{ ft}^2 \end{aligned}$$

For a 12 ft diameter vessel, the cross-sectional area of one adsorber is:

$$\text{Area of one adsorber} = \frac{(12 \text{ ft})^2 \pi}{4} = 113 \text{ ft}^2$$

Since there is only one adsorber per module in this example, the number of modules and adsorbers is:

$$\text{Number of adsorbers and adsorber modules} = \frac{1736 \text{ ft}^2}{113 \text{ ft}^2}$$

$$= 15.3$$

or 16

The volume of activated carbon in each adsorber for a bed depth of 16 ft is:

$$\begin{aligned} \text{Volume of activated carbon} &= 113 \text{ ft}^2 \times 16 \text{ ft} \\ \text{per adsorber} &= 1810 \text{ ft}^3 \end{aligned}$$

Assuming a 20% freeboard space in each adsorber, the volume of each adsorber vessel is:

$$\text{Volume of one adsorber} = \frac{1810 \text{ ft}^3}{0.80} = 2262 \text{ ft}^3$$

Refer to Figure 4-14. Select the 12 ft. diameter carbon steel adsorber with backwash Adsorber direct capital cost = 115 K\$.

For 16 adsorber modules, cost = $16 \times 115 \text{ K\$} = 1840 \text{ K\$}$. Total adsorber area is: $16 \times 113 = 1808 \text{ ft}^2$. Processing expenses from Figure 4-15 = 70 K\$/yr.

Initial carbon charge required = $16 \times 1810 \text{ ft}^3 \times 30 \text{ lb/ft}^3 = 868,800 \text{ lb}$.
Direct capital cost = $\$0.75 \times 868,800 \text{ lb} = 652 \text{ K\$}$.

Backwash

It is assumed that backwashing occurs sequentially throughout the system in only one adsorber vessel at a time. A backwash system is therefore sized for one adsorber based on flow cross-sectional area.

The adsorber area for a 12 ft diameter vessel is 113 ft².

The direct capital cost from Figure 4-22 = 64 K\$. Processing expenses from Figure 4-23 for 16 adsorber vessels = 9.4 K\$/yr.

Surface wash

Surface wash is not used in this example.

Regeneration System

The same considerations apply here as for selecting the regeneration rate for the drinking water treatment system discussed in Appendix A. Numbers here are, of course, different because the carbon exhaustion rate is different. Also, the 16 adsorber units will be brought on stream at 18 day intervals which is derived below.

Carbon exhaustion rate per adsorber:

$$\frac{300 \text{ lb} \times 10 \times 10^6 \text{ gal/day}}{10^6 \text{ gal} \times 16 \text{ adsorbers}} = 188 \text{ lb/day per adsorber}$$

Carbon weight per adsorber:

$$1810 \text{ ft}^3 \times 30 \text{ lb/ft}^3 = 54,300 \text{ lb}$$

Regeneration frequency per adsorber:

$$\frac{54,300 \text{ lb per adsorber}}{188 \text{ lb/day per adsorber}} = 289 \text{ days}$$

For the present case a maximum discharge interval can be calculated from the regeneration frequency and number of parallel adsorber modules.

$$\frac{289 \text{ days}}{16 \text{ adsorbers}} = 18 \text{ days per adsorber}$$

The minimum regeneration rate is therefore:

$$\frac{54,300 \text{ lbs per adsorber}}{18 \text{ days per adsorber}} = 3,007 \text{ lb/day.}$$

If the regenerator is sized for 50 percent over the minimum regeneration rate, the design regeneration rate is:

$$3,007 \text{ lb/day} \times 1.5 = 4,526 \text{ lb/day}$$

The direct capital cost for a multihearth regeneration system from Figure 4-34 = 810 K\$. Processing expenses from Figure 4-35 for an operating regeneration rate of 3007 lb/day = 90 K\$/yr.

Fresh Carbon Storage and Transfer

Every 289 days, during an 18 day period of regeneration, the total carbon regenerated is:

$$54,300 \text{ lb per adsorber} \times 16 \text{ adsorbers} = 868,800 \text{ lb.}$$

If carbon losses in this case are 5 percent the losses are:

$$.05 \times 868,800 \text{ lb} = 43,440 \text{ lbs per regeneration.}$$

The frequency of deliveries by a standard 40,000 lb truck is:

$$\frac{40,000 \text{ lb per delivery}}{43,440 \text{ lb/289 days}} = 266 \text{ days per delivery}$$

Assume a storage capacity equivalent to one standard truckload with 50 percent excess capacity:

$$1.5 \times \frac{40,000 \text{ lb}}{30 \text{ lb/ft}^3} = 2000 \text{ ft}^3$$

The direct capital cost for fresh storage and transfer equipment from Figure 4-2 = 60 K\$. Processing expenses depend on how much carbon is transferred. At a regeneration rate of 3007 lb/day and 5 percent losses, the average fresh carbon requirement is 150 lb/day. Processing expenses from Figure 4-3 = 1.2 K\$/yr.

Spent Carbon Storage and Transfer

Assume that the spent carbon storage volume is 50 percent greater than the volume of one adsorber. The spent carbon storage volume is then 3393 ft³.

The direct capital cost for carbon steel spent carbon storage and transfer equipment from Figure 4-2 = 80 K\$. Processing expenses at a regeneration rate of 3007 lb/day from Figure 4-3 = 2.8 k\$/yr

Regenerated Carbon Storage and Transfer

Assume regenerated carbon storage volume is equal to the spent carbon storage volume of 3393 ft³.

The direct capital cost for regenerated carbon storage and transfer from Figure 4-2 = 80 K\$. Processing expenses from Figure 4-3 = 2.8 k\$/yr.

Influent Pumping

The system design flow rate is 10 mgd. Assume a head requirement of 80 ft.

The direct capital cost for influent pumping from Figure 4-37 = 200 K\$. Processing expenses from Figure 4-38 = 90 K\$/yr.

Buildings and Site Preparation

Costs for buildings and for site preparation in Section 4 were based on standard design concepts defined there. Use of these costs requires an estimate of the areas for each. The area for buildings depends on how much of the GAC system is housed, and what additional requirements there are for offices, laboratories, and other facilities. Site preparation costs depend on total area including unhoused portions of the site.

Area estimates for computing both building and site preparation costs are obtained from estimates of process area. Area requirements for various process modules were provided in Figures 4-40 through 4-46.

For this case, the results are:

<u>Process Module</u>	<u>Area (ft)²</u>
Influent pumping	2,700
Fresh carbon storage	500
Spent carbon storage	600
Regenerated carbon storage	600

Adsorbers	5,200
Backwash	660
Regeneration	<u>850</u>
Process area required	11,110
Other (assume at 25% of process area)	<u>2,778</u>
Total area required	13,888

This area is used to calculate costs for site preparation. From Figure 4-46, the direct capital cost = 13 K\$.

For the estimate of building costs, assume only the adsorbers and regeneration system are housed. The minimum required building area is the process area of these modules. Assume an addition 20 percent for offices, control room, laboratory, and other facilities. The total building area required is:

$$6,050 \text{ ft} \times 1.2 = 7,260 \text{ ft}^2$$

From Figure 4-47, for a low cost building the direct capital cost = 190 K\$.

Building annual operating expenses include the costs of energy for lighting, heating, ventilating, air conditioning, and maintenance costs.

Energy costs depend on building area geographical location, and energy prices. Table 4-7 lists energy requirements for a number of major metropolitan areas. Assuming a St. Louis, Mo. location for this example, the energy expenses for the building are:

$$7260 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr} \times \$0.05/\text{kWh} = 50.3 \text{ K\$/yr.}$$

Assume annual maintenance expenses at 3 percent of direct capital cost. Maintenance expenses are:

$$.03 \times 190 \text{ K\$} = 5.7 \text{ K\$/yr.}$$

$$\text{Building annual operating expenses} = 56 \text{ K\$/yr.}$$

Carbon Losses

Carbon losses can range from 5 to 15 percent of the carbon regenerated. In this case, 5 percent has been assumed.

$$\text{Carbon losses} = .05 \times 3007 \text{ lb/day} \times 365 \text{ day/yr} = 54,878 \text{ lb/yr.}$$

Processing expense for carbon losses = $\$.75/\text{lb} \times 54,878 \text{ lb/yr} = 41.2 \text{ K\$/yr.}$

Interconnecting and Off-site Piping

Pipe sizes, lengths of lines, and valving needs must be estimated. Pipe sizes can be obtained from the flow rate and corresponding line sizes listed in Table 4-5.

Influent and effluent lines:

$$\frac{10 \times 10^6 \text{ gal/day}}{1440 \text{ min/day}} = 6944 \text{ gpm}$$

The line size from Table 4-5 = 24 inches.

Carbon slurry lines:

Carbon slurry lines are based on a standard transfer rate of 70 gpm of slurry. The line size from Table 4-5 = 3 inches.

Backwash lines (in and out):

Backwash lines depend on the adsorber size and backwash rate. At 18 gpm/ft³ for a 12 ft. diameter adsorber:

$$113 \text{ ft}^3 \times 18 \text{ gpm/ft}^3 = 2034 \text{ gpm.}$$

The line size from Table 4-5 = 14 inches.

Surface wash lines:

No surface wash is used in this example.

Service lines for compressed air and plant water:

Assume 2.0" line size for services to the process area.

The lengths of these lines depends on individual plant layout and spacing of units to be interconnected. Once lengths have been established, costs for piping are obtained from Table 4-1. For each individual installation, the number of valves must also be specified. Here it is assumed that two valves are required in each line. Costs for valves are obtained from Table 4-2.

A summary for interconnecting and off-site piping is given below:

Direct Capital Cost (K\$)				
<u>Line</u>	<u>Size(in)</u>	<u>Length(ft)</u>	<u>Piping</u>	<u>Valves</u>
Influent	24	250	25	30
Effluent	24	250	25	30
Carbon slurry lines	3	250	2.3	3.1
Backwash in	14	250	12	9.4
Backwash out	14	250	12	9.4
Services	2	500	<u>6.0</u>	<u>1.8</u>
			81.3	+ 83.7 = 166 K\$

Annual maintenance expenses at 1 percent per year = 1.7 K\$/yr.

Electrical Supply and Distribution

An estimate of total installed electrical requirement is obtained by summing the major power requirement for the power consuming modules. An allowance of 20 percent over this value is provided as a design contingency. Major system power requirements are for influent pumping, backwash pumping, carbon slurry transfers, regeneration, and building needs.

Power needs for each module are as follows:

Influent pumping:

Power is for pumping influent water to the adsorbers.

Power = 0.52 x flow rate in mgd x pumping head in psig

In this case, Power = 0.52 x 10 x 34 = 177 kW

Carbon storage and transfer:

Power needs are for pumping carbon slurries during various transfer operations between the adsorbers and storage vessels. Power needs between carbon storage and regeneration are included under regeneration power requirements.

The power required for carbon slurry transfer depends on whether an educator or direct pump system is used for transfer, the slurry concentration, with

the rate at which the slurry is pumped, and the pumping head. Power for the eductor is supplied to the motive water pump. In direct pump systems, power is supplied directly to the slurry pumps themselves.

In this report, the basis for slurry transfer power needs is a fixed transfer rate of 70 gpm of slurry.

For an eductor system, the motive water required is 5 times the process stream rate for a total of 350 gpm. The motive water must be supplied at a head pressure 60 psig above the eductor discharge pressure. For a discharge of 32 psig used in this report, the motive water supply pump head pressure is 92 psig.

$$\text{Pumping power} = .0075 \times \text{gpm} \times \text{psig}$$

Eductor power is therefore:

$$\text{Power} = .00075 \times 350 \times 92 = 24 \text{ kW}$$

For a direct pump system, the power at a discharge of 32 psig is :

$$\text{Power} = .00075 \times 70 \times 32 = 1.7 \text{ kW.}$$

Since it is unlikely that the intermittent carbon transfers between adsorbers and storage will occur simultaneously, the installed power requirements calculated above are sufficient, even though three separate types of storage are involved.

Backwash:

Power for the backwash system depends on the pumping rate and pumping head requirement. The pumping rate depends on individual adsorber area and the backwash flow rate per unit adsorber area. Pumping head depends on overall system design. In this report, backwash costs are based on a backwash flow rate per unit adsorber area of 18 gpm/ft² and an assumed pumping head requirement of 22 psig.

$$\text{Power} = .00075 \times 18 \times 22 \times \text{individual adsorber area in ft}^2.$$

In this case, the individual adsorber area is 113 ft².

$$\text{Power} = .00075 \times 18 \times 22 \times 113 = 34 \text{ kW}$$

Surface wash:

Considerations for the surface wash system are analogous to those for the backwash system, except that the pumping rate is lower and pumping head is higher to accommodate the higher head losses in a spray header system. In this

report, the surface wash flow rate per unit adsorber area is 1.5 gpm/ft² with an assumed pumping head of 86 psig.

$$\text{Power} = .00075 \times 1.5 \times 86 \times \text{individual adsorber area in ft}^2.$$

In this case, no surface wash was used so that calculation of a requirement is unnecessary.

Regeneration:

Power required for regeneration depends on regeneration rate and the type of regeneration system.

Requirements for the multihearth system considered in this report are:

$$\text{Multihearth power} = 5.9 \times 10^{-3} \text{ kW/lb/day} \times 4526 \text{ lb/day} = 27 \text{ kW}$$

Buildings:

The power required for buildings depends on size, location, and specific needs for heating, lighting, ventilation, and air conditioning. Average needs were given in Table 4-7.

In this case, the building area is 7,760 ft². A single-story building is specified. Assuming a St. Louis, MO location, the power requirement is:

$$\text{Power} = \frac{7,760 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr}}{8760 \text{ hr/yr}} = 123 \text{ kW}$$

Total Installed Power Requirement:

Adding the above and applying a factor of 1.2, the total is:

$$385 \text{ kW} \times 1.2 = 462 \text{ kW}.$$

The direct capital cost for an electrical substation and distribution system from Figure 4-39 = 28 K\$.

Annual maintenance expenses at 2 percent of direct capital cost = 0.6 K\$/yr.

APPENDIX C

CALCULATIONS FOR INDUSTRIAL WASTEWATER TREATMENT SYSTEM

APPENDIX C

CALCULATIONS FOR INDUSTRIAL WASTEWATER TREATMENT SYSTEM EXAMPLE AT 10 MGD

Adsorbers

Empty bed contact time: 60 min

Hydraulic loading: 4 gpm/ft²

Total bed depth:

$$\frac{4 \text{ gpm/ft}^2 \times 60 \text{ min}}{7.5 \text{ gal/ft}^3} = 48 \text{ ft}$$

Pulsed bed adsorbers are used in this case study. Each adsorber contain 48 ft of activated carbon. Assuming a 20 percent freeboard the adsorber vessel height is 60 ft.

The total adsorber cross-sectional area can be found from the hydraulic loading (4gpm/ft²) and the flow rate to the treatment system.

$$\text{Total cross-sectional area} = \frac{10 \times 10^6 \text{ gal}}{\text{day}} \times \frac{1 \text{ day}}{1440 \text{ min}} \div (4 \text{ gpm/ft}^2) = 1726 \text{ ft}^2$$

For a 12 ft diameter vessel, the cross-sectional area of one adsorber is 113.1 ft². Since there is only one adsorber per module, the total number of parallel modules and adsorbers is:

$$\text{Number of adsorbers and adsorber modules} = \frac{1736 \text{ ft}^2}{113 \text{ ft}^2} = 15.3$$

Next larger whole number = 16

The volume of activated carbon in each adsorber for a bed depth of 48 ft is:

$$\text{Volume of activated carbon} = 113 \text{ ft}^2 \times 48 \text{ ft} = 5429 \text{ ft}^3 \text{ per adsorber}$$

$$\text{Initial carbon charge} = 16 \times 5429 \text{ ft}^3 \times 30 \text{ lb/ft}^3 = 2,605,920 \text{ lb}$$

$$\text{Direct capital cost} = \$0.75 \times 2,605,920 \text{ lb} = 1,954 \text{ K\$}$$

Assuming a 20 percent freeboard space in each adsorber, the volume of each adsorber vessel is:

$$\text{Volume of one adsorber} = \frac{5429 \text{ ft}^3}{0.80} = 6786 \text{ ft}^3$$

Refer to Figure 4-17. Select a 12 ft. diameter carbon steel adsorber without backwash. The direct capital cost per adsorber = 230 K\$. For 16 adsorbers, the direct capital cost = 3680 K\$. Total adsorber area is: $16 \times 113 = 1808 \text{ ft}^2$. Processing expenses from Figure 4-18 = 70 K\$/yr.

Backwash

Backwash is not used in this example.

Surface wash

Surface wash is not used in this example.

Regeneration System

For pulsed bed adsorbers, spent carbon is discharged at appropriate intervals and transferred to a spent carbon storage tank. The regeneration system operates continuously while drawing feed carbon from this storage tank.

The carbon exhaustion rate per adsorber at a carbon dosage of 1000 lb/10⁶ gal is:

$$\frac{1000 \text{ lb} \times 10 \times 10^6 \text{ gal/day per adsorber}}{10^6 \times 16 \text{ adsorbers}} = 625 \text{ lb/day per adsorber}$$

The carbon weight per adsorber:

$$5429 \text{ ft}^3 \times 30 \text{ lb/ft}^3 = 162,870 \text{ lb}$$

Total weight of exhausted carbon from all adsorbers per day:

$$625 \text{ lb/day} \times 16 = 10,000 \text{ lb/day.}$$

Minimum regeneration rate is therefore, 10,000 lb/day.

Size the regeneration system for 50 percent over the minimum regeneration rate. The design rate is:

$$10,000 \text{ lb/day} \times 1.5 = 15,000 \text{ lb/day}$$

For this example a fluid bed regeneration system is used. The regeneration system direct capital cost from Figure 4-32 = 1100 K\$.

Processing expenses at the operating rate of 10,000 lb/day = 105 K\$/yr.

Fresh Carbon Storage and Transfer

At a regeneration rate of 10,000 lb/day and carbon losses of 5 percent, the daily fresh carbon requirement = 500 lb/day.

The frequency of deliveries by a standard 40,000 lb truck is:

$$\frac{40,000 \text{ lb per delivery}}{500 \text{ lb/day}} = 80 \text{ days per delivery}$$

Assume storage capacity equivalent to one standard truckload with 50 percent excess capacity.

$$1.5 \times \frac{40,000 \text{ lb}}{30 \text{ lb/ft}^3} = 2000 \text{ ft}^3$$

Direct capital cost for carbon steel fresh carbon storage and transfer equipment from Figure 4-2 = 60 K\$.

Processing expenses at 500 lb/day of carbon transferred from Figure 4-3 = 1.3 K\$/yr.

Spent Carbon Storage and Transfer

Assume that the spent carbon storage volume is equivalent to 10-days of regeneration operating capacity. The spent carbon storage volume is then:

$$\frac{10,000 \text{ lb/day}}{30 \text{ lb/ft}^3} \times 10 \text{ days} = 3333 \text{ ft}^3$$

The direct capital cost for carbon steel spent carbon storage and transfer from Figure 4-2 = 30 K\$. Processing expenses from Figure 4-3 for 10,000 lb/day = 2.7 K\$/yr.

Regenerated Carbon Storage and Transfer

This is essentially a duplication of the spent carbon storage and transfer equipment.

The direct capital cost for regenerated carbon storage and transfer from Figure 4-2 = K\$. Processing expenses from Figure 4-3 for 10,000 lb/day = 2.7 K\$/yr.

Influent Pumping

The system design flow rate is 10 mgd. Assume head requirement of 80 ft.

The direct capital cost for influent pumping from Figure 4-37 = 200 K\$.

Processing expenses from Figure 4-38 = 90 K\$/yr.

Buildings and Site Preparation

Costs for buildings and for site preparation in Section 4 were based on standard design concepts defined there. Use of these costs requires an estimate of the areas for each. The area for buildings depends on how much of the GAC system is housed, and what additional requirements there are for offices, laboratories, and other facilities. Site preparation costs depend on total area including unhoused portions of the site.

Area estimates for computing both building and site preparation costs are obtained from estimates of process area. Area requirements for various process modules were provided in Figures 4-40 through 4-46.

For this case, the results are:

<u>Process Module</u>	<u>Area (ft)²</u>
Influent pumping	2,700
Fresh carbon storage	500
Spent carbon storage	200
Regenerated carbon storage	200
Adsorbers	5,200
Regeneration	<u>1,700</u>
Process area required	10,500
Other (assume at 25% of process area)	<u>2,625</u>
Total area required	13,125

This area is used to calculate costs for site preparation. From Figure 4-46 the direct capital cost = 13 K\$.

For the estimate of building costs, assume that only influent pumping is housed. Also assume that an additional 20 percent of the total required process area is required for offices, control room, laboratory, and other facilities. The total building area required is:

$$(10,500 \text{ ft}^2 \times 0.2) + 2700 = 5850 \text{ ft}^2$$

From Figure 4-47, using costs for low cost buildings, the direct capital cost = 150 K\$.

Building annual operating expenses include the costs of energy for lighting, heating, ventilating, air conditioning, and maintenance costs.

Energy costs depend on building area, geographical location, and energy prices. Table 4-7 lists energy requirements for a number of major metropolitan areas. Assuming a St. Louis, Mo. location for this example, the energy expenses for the building are:

$$5,850 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2 \text{ yr} \times \$0.05/\text{kWh} = 41 \text{ K\$}/\text{yr}$$

Assume annual maintenance expenses at 3 percent of direct capital cost. Maintenance expenses are:

$$.03 \times 150 \text{ K\$} = 4.5 \text{ K\$}/\text{yr}$$

Building annual operating expenses = 46 K\$ / yr.

Carbon Losses

Carbon losses can range from 5 to 15% of the carbon regenerated. In this case, 5% has been assumed.

$$\text{Carbon losses} = .05 \times 10,000 \text{ lb/day} \times 365 \text{ day/yr} = 182,500 \text{ lb/yr}$$

$$\text{Processing expense for carbon losses} = \$0.75/\text{lb} \times 182,500 \text{ lb/yr} = 137 \text{ K\$}/\text{yr}.$$

Interconnecting and Off-site Piping

Pipe sizes, lengths of lines, and valving needs must be estimated. Pipe sizes can be obtained from the flow rate and corresponding line sizes listed in Table 4-5.

Influent and effluent lines:

$$\frac{10 \times 10^6 \text{ gal/day}}{1440 \text{ min/day}} = 6944 \text{ gpm}$$

The line size from Table 4-5 = 24 inches.

Carbon slurry lines:

Carbon slurry lines are based on a standard transfer rate of 70 gpm of slurry. The line size from Table 4-5 = 3 inches.

Backwash lines (in and out):

No backwash is used in this example.

Surface wash lines:

No surface wash is used in this example.

Service lines for compressed air and plant water:

Assume 2.0" line size for services to the process area.

The lengths of these lines depend on individual plant layout and spacing of units to be interconnected. Once lengths have been established, costs for piping are obtained from Table 4-1. For each individual installation the number of valves must also be specified. Here it is assumed that two valves are required in each line. Costs for valves are obtained from Table 4-2.

A summary for interconnecting and off-site piping is given below:

<u>Line</u>	<u>Size</u>	<u>Length</u>	<u>Direct Capital Cost (K\$)</u>	
			<u>Cost</u>	<u>Valves</u>
Influent	24	250	25	30
Effluent	24	250	25	30
Carbon slurry	3	250	2.3	3.1
Services	2	500	<u>6.0</u>	<u>1.8</u>
			58.3	+ 64.9 = 123 K\$

Electrical Supply and Distribution

An estimate of total installed electrical requirement is obtained by summing major power requirement for power consuming modules. An allowance of 20 percent over this value is provided as a design contingency. Major system power requirements are for influent pumping, backwash pumping, carbon slurry transfers, regeneration, and building needs.

Power needs for each module are as follows:

Influent pumping:

Power is for pumping influent water to the adsorbers.

Power = 0.52 x flow rate in mgd x pumping head in psig

In this case,

Power = 0.52 x 10 x 34 = 177 kW

Carbon storage and transfer:

Power needs are for pumping carbon slurries during various transfer operations between the adsorbers and storage vessels. Power needs between carbon storage and regeneration are included under regeneration power requirements.

The power required for carbon slurry transfer depends on whether an eductor or direct pump system is used for transfer, the slurry concentration used, the rate at which the slurry is pumped, and on the pumping head. Power for the eductor is supplied to the motive water pump. In direct pump systems, power is supplied directly to the slurry pumps themselves.

In this report, the basis for slurry transfer power needs is a fixed transfer rate of 70 gpm of slurry.

For an eductor system, the motive water required is 5 times the process stream rate for a total of 350 gpm. The motive water must be supplied at a head pressure 60 psig above the eductor discharge pressure. For a discharge of 32 psig used in this report, the motive water supply pump head pressure is 92 psig.

$$\text{Pumping power} = .00075 \times \text{gpm} \times \text{psig}$$

Eductor power is therefore:

$$\text{Power} = .00075 \times 350 \times 92 = 24 \text{ kW}$$

For a direct pump system, the power at a discharge of 32 psig is :

$$\text{Power} = .00075 \times 70 \times 32 = 1.7 \text{ kW.}$$

Since it is unlikely that the intermittent carbon transfers between adsorbers and storage will occur simultaneously, the installed power requirements calculated above are sufficient, even though three separate types of storage are involved.

Backwash:

No backwash system was used in this case.

Surface wash:

No surface wash system was used in this case.

Regeneration:

Power required for regeneration depends on regeneration rate and the type of regeneration system.

Requirements for the fluid bed systems considered in this report are:

$$\text{Fluid bed power} = 4.7 \times 10^{-3} \text{ kW/lb/day} \times 15,000 \text{ lb/day} = 70 \text{ kW}$$

Buildings:

The power required for buildings depends on size, location, and specific needs for heating, lighting, ventilation, and air conditioning. Average needs were given in Table 4-7.

In this case, the building area is 5,850 ft. A single story building is specified. Assuming a St. Louis, MO location, the power requirement is:

$$\text{Power} = \frac{5,850 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr}}{8760 \text{ hr/yr}} = 93 \text{ kW}$$

Total Installed Power Requirement:

Adding the above and applying a factor of 1.2, the total is:

$$364 \text{ kW} \times 1.2 = 437 \text{ kW.}$$

The direct capital cost for an electrical substation and distribution system from Figure 4-39 = 27 K\$.

Annual maintenance expenses at 2 percent of direct capital cost = 0.5 K\$/yr.

APPENDIX D

**NOTES ON COSTS FOR VESSELS,
PUMPS, PIPING, AND VALVES**

APPENDIX D

NOTES ON COSTS FOR VESSELS, PUMPS, PIPING, AND VALVES

This appendix provides some of the details on data sources and estimates for the capital costs of some equipment. It discusses:

- vessel cost
- individual pump and pump station costs, and
- piping and valve costs

D.1 Vessel Costs

Costs were developed for several kinds of vessels required for granular activated carbon systems:

- adsorber vessels
- storage vessels, and
- transfer vessels (hoppers and blowcases).

Adsorber vessels are made of both steel and concrete. Steel vessels may be designed for atmospheric pressure or pressures above atmospheric and may be closed or opened with different types of heads and bottoms. Various materials of construction and/or vessel liners can be used. Table D-1 summarizes the vessel types considered in this report.

Costs were estimated for each of these vessel types for selected individual sizes and the costs curves of Section 4 drawn from these estimates. For steel vessels estimates were made for diameters of 8, 10, and 12 ft. with heights of 15, 30, and 60 ft., and a 50 psig rating. Costs for large open vessels of 20 ft. and 30 ft. diameter were adjusted and updated from Reference 1. Purchased costs for pressure steel vessels were estimated using the methods found in Reference 2. In this procedure, individual vessel components are estimated separately and added together to obtain the total purchased cost. Table D-2 lists the individual components used to estimate complete vessel costs.

Installation costs were estimated separately and added to the purchased costs to obtain the total direct cost. Installation costs for steel vessels were computed using an installation factor which was multiplied by the vessel purchase cost for carbon steel vessels. The installation factor used in this report was derived from the 'norm' installation factor given in Reference 3. A comparison between the factor actually given in Reference 3 and the factor

used in this report is shown in Table D-3. This factor was applied to steel adsorption vessels. Piping costs were estimated separately for conceptual piping layouts for selected size vessels using methods discussed in Section D4. Factors were then developed from these estimates for piping as a percentage of purchase cost and as a function of vessel volume.

Installation costs for pressure steel adsorbers in this report are also compared here with costs from Reference 1. Table D-4 provides component breakdown for installation estimates of these adsorber costs in the reference and this report.

Differences in the various factors for cost elements occur due to differences in estimating methods. This report used factors presented for vessels in Reference 3 as discussed above, modified to allow for a separate estimate of piping materials and labor. In the table, the factor for piping and values shown for Reference 1 applies to materials only, with the labor for piping included in the overall labor factor. In this report, the factor developed for piping includes piping materials and labor. The labor factor that was shown in Table D-3 is for all other installation labor.

Figure D-1 compares individual adsorber vessel costs from this report with Reference 1 after adjustment of Reference 1 costs to the common basis of direct capital cost.

Concrete adsorption vessel costs were also estimated using methods from Reference 2. Costs for platforms, piping and other accessories were estimated separately from the costs of the concrete structure. No installation factor was used for concrete vessels as the estimate is for field construction. Costs for excavation, concrete work, platforms and walkways were obtained from Reference 2. Costs for piping were estimated separately in the same manner as for steel vessels.

Storage vessel costs were estimated using the same procedures as for adsorbers except that the selected vessel sizes used for the estimates and constructing the cost curves were different and only open top steel vessels were considered. For concrete storage vessels, closed top concrete vessels were considered. Piping associated with storage vessels was estimated separately from conceptual designs for selected sizes and factors developed for other size vessels.

Transfer vessels included hoppers used as slug feed tanks for pulsed bed adsorbers and blowcases for slurry transfer. Hoppers were essentially identical with storage vessels except they were smaller in size. Blowcases were small pressure vessels with an elliptical top and conical bottom. Costs for both types of vessels were estimated using the same procedure as for larger storage and pressure vessels.

All vessel costs were updated from the references using the CE Plant Cost Index.

D.2 Individual Pump Costs

Pumps are a vital part of a GAC plant. Pumps are required for pumping of influent water, backwash, and carbon slurry. The most common pump in use is the centrifugal pump. Two fundamental types of centrifugal pumps that would be found in a GAC system are the standard general purpose type and the turbine type. Turbine pumps are more efficient than standard centrifugal pumps for achieving high heads at high flow rates. They, therefore, might be used rather than centrifugal pumps in larger facilities. Centrifugal pump costs were used in this report, however.

Pump costs for this report were obtained from Reference 3 and were compared with References 2 and 4.

Updated costs from Reference 3 were used for influent pump stations. These pump costs were the highest of those obtained from these literature sources. However, this probably occurs because the pumps are designed to API specifications which means that they are able to withstand relatively severe service. All pump costs were updated to September, 1980 using the CE Cost Index for Pumps and Compressors. Costs include the pump and driver, and peripherals as discussed below.

Curves for direct costs of pumps were constructed based on estimates for several sizes each for both influent station pumps and the other pumps. Individual pump costs were combined with piping, vessel, and other costs as appropriate for estimating total direct costs for the modules of influent pumping, carbon storage and transfer, and filter washes (backwash and surface wash).

Installation costs for pumps were obtained by multiplying the purchased equipment cost by a factor adapted from Reference 3. Table D-5 shows material and labor components comprising the installation factor for pumps and drivers.

D.3 Influent Pump Stations

Costs for influent pump stations appropriate for granular activated carbon projects were provided in several references. Reference 5 presented influent pump station costs for a granular activated carbon plant based on costs of the South Tahoe project. The system design specifications were not provided, however. Reference 1 presented pump station costs for in-plant pumping, raw-water pumping, and packaged pump stations for influent pumping.

As discussed previously, individual pump costs for influent pump stations were obtained from Reference 3. The influent pump station consists of at least three pumps, two for operation sized at one-half the total required flow rate, and one spare pump of the same size. The maximum pump size used in this study was 7000 gpm. For flow rates greater than this gpm, several pumps were used; these were sized as an even multiple of total flow rate with one spare pump of the same size.

The pump cost was based on an estimated concrete pump providing 60 min holding time for influent water at design flow.

D.4 Piping Costs

Piping costs used in this report are based on updated piping costs from Reference 3 after comparisons with costs reported in other literature sources (2, 4, 6). Costs for piping were developed on a per foot installed cost basis which corresponds to the direct cost for piping in accordance with the capital cost format used throughout this report. The unit piping costs represent the cost for materials and labor of straight run pipe, a typical complement of fittings, and supports such as pipe hangers and brackets. In order to express costs as dollars per foot of straight run, while including the cost of fittings, the contribution of fittings to a pipe system installation had to be estimated on an average basis.

Two general types of piping configurations defined for developing costs in this way are simple and complex systems (6). These systems differ in the number of turns and branches and hence in the average number of fittings required per length of straight run. Adsorber piping for granular activated carbon installations fits the criteria for complex piping. The complex piping costs were applied to adsorber piping conceptual designs in order to estimate piping costs for adsorbers. The simple configurations would apply to storage vessels, concrete adsorbers, and interconnecting and offsite piping. Table D-6 compares the unit piping costs developed for simple and complex configurations based on straight run and fitting costs from several references.

The unit piping costs were used for the following estimates:

- piping associated with adsorbers,
- piping associated with other process modules, and
- interconnecting or interface piping between the subsystems of the GAC system, and between the GAC system and other parts of an overall facility of which the GAC system is a part.

Unit piping costs do not include valves. These must be counted separately and added to the costs of piping for any module. Piping material costs were updated from the mid-1970 values of Reference 3 to September, 1980 using the CE Cost Index for Piping, Fittings and Valves. Installation labor requirements were estimated from Reference 3 and labor rates obtained from Engineering New Record (7).

Costs were estimated for carbon steel and stainless steel systems. Other materials such as carbon steel with plastic liners and plastic pipe can be used but costs for these materials are not included in this report.

D.5 Valve Costs

Like piping costs, valve costs used in this report are based on updated costs from Reference 3 after comparisons with costs reported in other literature sources (3, 4). The gate valve was selected as the basis for all valve costs as costs on gate valves are readily available and costs for other valves can be readily related to the gate valve by a factor. A comparison of reported gate valve costs from the literature for several sizes is given in Table D-7. Costs for other types of valves^a used in a GAC plant can run from about 45 percent less to about 40 percent more than manual gate valves based on information from Reference 8.

In a GAC system, some valves will be manual and some automatic. Air cylinder or electrically-activated solenoid valves might be employed for on-off service. Larger valves and those used for throttling or flow control might use either air actuators or be motor driven. It is anticipated that proportional control valves would be used sparingly in a GAC plant, perhaps to control influent flow rate to the adsorber but not for other lines. Reference 8 indicates that costs for air operated or motor driven valves are about 40 percent more than a comparable manual valve.

^aDiaphragm, pinch, rubber lined plug, and knife gate types.

APPENDIX E

**COMPARISON BETWEEN COSTS REPORTED FOR ACTUAL
4 MGD GAS PLANT AND ESTIMATED COSTS**

APPENDIX E
COMPARISON BETWEEN COSTS REPORTED FOR ACTUAL
4 MGD GAC PLANT AND ESTIMATED COSTS

A GAC demonstration project was recently completed within the last year at a municipal drinking water treatment plant in Cincinnati, Ohio (9). Reported design and cost information was compared to results obtained using the methodology and costs of this report. Comparative cost summaries between reported and estimated costs are presented here in tables for direct capital costs and processing expenses. Major differences between reported costs and estimated costs are briefly explained. A complete comparison would require a cost analysis beyond the scope of this report. Design calculations for this system, and selection of appropriate modular costs from the costs of this report are presented in the same format as the examples in Appendices A, B, and C.

This comparison clearly illustrates where cost differences may arise between systems. It is apparent that there are differences in scope, design details, prices, and accounting (cost formatting) procedures. While individual components sometimes show some large differences, the totals show reasonable agreement for both the capital costs and annual processing expenses.

Direct Capital Cost Comparison

The direct capital cost comparison is summarized in Table E-1. A large difference is apparent in the influent pumping costs. The actual project appears to have used pumps and a pump process area already available in the existing overall water plant. This influent pump system used two pumps with a combined capacity of 3 mgd for the GAC adsorber influent, although the adsorber system was designed for a 4 mgd capacity. The standard pump station of the current report has three pumps (two operating and one spare) and a sump. The total design flow used for the example estimate of this report is also designed for a flow of 4 mgd rather than 3 mgd. This difference can account for some of the discrepancy in influent pumping costs.

Adsorber costs were estimated lower than reported costs. This is attributed to some special features of the actual adsorbers designed for data acquisition which may have increased complexity due to provisions for additional nozzles as sampling ports. Estimated regeneration costs are higher than reported. This is due to both higher estimated purchased equipment costs and installation. The vendor of regeneration equipment was contacted but was unable to provide additional information.

Regeneration system cost differences may reflect differences in the bidding and pricing of a specific project versus a reported cost from a previously-published cost estimating manual. As the fluid-bed regeneration

TABLE E-1. DIRECT CAPITAL COST COMPARISON FOR CINCINNATI PROJECT

Flow rate: 4 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 15 min	Regeneration type: fluid-bed
CD: -	Cost base year: September 1980 (for estimate) ^a

	Cost (\$1000)	
	Reported Cincinnati Project	Estimated This Report
<u>Battery Limits</u>		
Influent Pumping	37	125 ^b
Adsorbers	650	480
Initial Carbon Charge	86	86
Regeneration System	599 ^c	1100 ^c
Fresh Carbon Storage and Transfer	-	-
Spent Carbon Storage and Transfer	-	65
Regenerated Carbon Storage and Transfer	-	65
Backwash System	-	55
Surface Wash System	-	-
Other	54	-
Subtotal Battery Limits	1426	1976
<u>Auxiliaries and Offsites</u>		
Buildings	314	170
Interconnecting and Offsite Piping	-	71
Electrical Supply and Distribution	-	40
Site Preparation	-	10
Other	123	-
Subtotal Auxiliaries and Offsites	442	291
TOTAL DIRECT CAPITAL COST	1868	2267

^a Reported costs were stated as applicable for the period of 1979-1980.

^b Costs in this estimate are based on a standard design configuration of three pumps and a sump. Each pump is sized at 50 percent of total flow with one spare. Use of fewer pumps, and elimination of a sump will substantially reduce costs for this item. Individual pump prices are also subject to wide variations depending on design details.

^c Attempts were made to reconcile these apparent differences. One difference was that estimated installation requirements were greater than those actually reported for the specific actual installation. The vendor of the regeneration system was contacted but could not provide any additional information.

system is not a mass-produced product, its cost is probably subject to substantial variability. The estimate using the current manual does appear high, however, especially when carbon storage and transfer facilities are added which are already included in the lower figure for the actual project.

The overall difference between the reported and estimated costs result in the estimated battery limit costs being about 39 percent higher than the reported costs.

Under auxiliaries and offsites, reported building costs are about 8 percent higher than estimated building costs. Since detailed specifications are not available in either case, this comparison cannot be explored further. A comparison of the subtotal for auxiliaries and offsites shows that estimated costs are about 34 percent lower than reported costs, with the difference in building costs accounting for much of the difference.

Processing Expense Comparison

Processing expenses are compared in Table E-2. Estimated total processing expenses are about 29 percent higher than reported processing expenses.

Costs for influent pumping reflect the difference in pumping rate, pump efficiencies, and pumping head specifications. The reported pumping rate was 3 mgd although the plant was designed for 4 mgd operation. The estimated cost was based on 4 mgd. Pumping heads and efficiencies for the reported costs were unknown so no comparison could be made to estimated bases. The reported electricity cost was \$.025/kWh while the estimated cost was \$.05/kWh.

Reported costs for the adsorbers include the cost of makeup carbon (identified as the expense of carbon losses in the present report). In the present report the expense of carbon losses is presented as a separate item. If this expense is combined with adsorber expenses the combined value of 92 K\$/yr is 4 percent lower than the reported value of 96 K\$/hr. Estimated regeneration expenses are about 28 percent lower than reported expenses. Expenses for carbon storage and transfer, and for backwashing were not reported separately, but were combined in the reported expenses for the adsorbers and regeneration system. For the estimate, these expenses were reported separately. A similar situation applies under the auxiliaries and offsites category. One large difference in this category is in the expenses for the building. This is attributable primarily to the use of the suggested values for energy consumption from Table 4-7 and to the approximation of the Cincinnati location by using the St. Louis, Missouri. The values in Table 4-7 were obtained from a reference and may be somewhat high. Also, the estimated electricity price is higher than the reported value for the Cincinnati project as noted previously. This difference in building expenses above accounts for 42 percent of the total difference between the estimated and reported costs.

TABLE E-2. PROCESSING EXPENSE COMPARISON FOR CINCINNATI PROJECT

Flow rate: 4 mgd	Adsorber type: fixed-bed, pressure steel, downflow
EBCT: 15 min	Regeneration type: fluid-bed
CD: -	Cost base year: September 1980 (for estimate) ^a

	Cost (\$1000)	
	Reported Cincinnati Project	Estimated This Report
<u>Battery Limits</u>		
Influent Pumping	12.7	48.0
Adsorbers	95.9	32.0
Regeneration System	59.5 ^b	43.0
Carbon Losses	-	60.2 ^d
Fresh Carbon Storage and Transfer	n.i. ^c	n.i. ^c
Spent Carbon Storage and Transfer	- ^e	4.0
Regenerated Carbon Storage and Transfer	- ^e	4.0
Backwash System	- ^e	4.8
Subtotal Battery Limits	167.8	196.0
<u>Auxiliaries and Offsites</u>		
Buildings	7.6	29.0
Interconnecting and Offsite Piping	-	0.7
Electrical Supply and Distribution	-	0.5
Subtotal Auxiliaries and Offsites	7.6	30.2
TOTAL PROCESSING EXPENSES	175.4	226.2

^aReported costs were stated as applicable for the period of 1979-1980.

^bCost of carbon losses (carbon makeup) appear to be included with adsorbers.

^cn.i. = not included.

^dCarbon losses were reported as 15%. At 2300 lb/day annual daily average rate, and 365 days/yr operation, total losses are: $2200 \times .15 \times 365 = 120,450$ lb/yr. At \$0.50/lb, the price used for the Cincinnati project annual expense for carbon makeup = $120,450 \times 0.50 = \$60.2$ thousand per year.

^eIncluded in costs of other items.

Calculations for Comparative Example

Adsorbers

Empty bed contact time = 15 min.

Hydraulic loading = 7.4 gpm/ft²

Total bed depth required:

$$\frac{7.4 \text{ gpm/ft}^2 \times 15 \text{ min.}}{7.5 \text{ gal/ft}^3} = 14.8 \text{ ft (call 15)}$$

The configuration is four adsorbers in parallel. The determination of the required number of parallel adsorbers is shown below.

The total adsorber cross-sectional area can be found from the hydraulic loading and the feed rate to the treatment system. For a total flow rate of 4 mgd and a hydraulic loading of 7.4 gpm/ft², the total adsorber cross-sectional area is:

$$\begin{aligned} \text{Total cross-sectional area} &= \frac{(4 \times 10^6 \text{ gal/day}) \times (1 \text{ day}/1440 \text{ min})}{7.4 \text{ gal/min ft}^2} \\ &= 375 \text{ ft}^2 \end{aligned}$$

The number of individual parallel adsorber modules can be found from the total cross-sectional area. An 11 ft diameter adsorber vessel is specified as the diameter used for the Cincinnati project.

$$\text{Area of one adsorber} = \frac{(11 \text{ ft})^2 \pi}{4} = 95 \text{ ft}^2$$

$$\begin{aligned} \text{Number of adsorber vessels} &= \frac{375 \text{ ft}^2}{95 \text{ ft}^2} \\ &= 3.95 \quad (\text{call } 4) \end{aligned}$$

Four (4) vessels in parallel are required to accommodate the total design flow.

The volume of activated carbon in each adsorber is:

$$\begin{aligned} \text{Volume activated carbon per adsorber} &= 95 \text{ ft}^3 \times 15 \text{ ft} \\ &= 1425 \text{ ft}^3 \end{aligned}$$

Assuming an adsorber freeboard volume of 32 percent, the volume of the adsorber vessel is:

$$\text{Volume of one adsorber} = \frac{1425 \text{ ft}^3}{0.68} = 2096 \text{ ft}^3$$

This corresponds to an adsorber height of 22 ft.

Refer to Figure 4-14. By interpolation, select the 11 ft diameter carbon steel adsorber with backwash. The direct capital cost for one adsorber = 120 K\$. Total adsorber area is: $4 \times 95 \text{ ft}^2 = 375 \text{ ft}^2$. Processing expenses from Figure 4-15 = 32 K\$/yr.

For 4 adsorber vessels, the direct capital cost is: $4 \times 120 \text{ K\$} = 480 \text{ K\$}$.

Initial Carbon Charge

Initial carbon charge required = $4 \times 1425 \text{ ft}^2 \times 30 \text{ lb/ft}^2 = 171,000 \text{ lb}$, at a bulk density of 30 lb/ft^3 .

At a carbon price of \$0.50 per lb, direct capital cost = $0.50 \times 171,000 = 86 \text{ K\$}$.

Backwash

It is assumed that backwash occurs sequentially throughout the system in only one adsorber vessel (not module of two vessels) at a time. The backwash system is therefore sized for only one adsorber vessel. Direct capital cost depends only on the cross-sectional area of the individual adsorber. But, processing expenses for a GAC backwash system depend on how many vessels there are in the system since the system expenses are the sum of the expenses for the individual vessels.

The adsorber area for an 11 ft diameter vessel is 95 ft^2 .

The direct capital cost for a backwash system with backwash wastewater storage = 55 K\$.

Processing expenses for 4 adsorber vessels = 4.8 K\$/yr.

Regeneration System

A fluid-bed regeneration system is used. In this example, the regeneration rate is provided from data on the actual system. Therefore, the calculation procedures based on carbon dosage used in the examples of Appendices A, B, and C are not necessary.

The design regeneration rate is 14,040 lb/day and the operating regeneration rate is 12,000 lb/day. These are not annual average rate, however, because the regeneration in this case is designed for intermittent operation. The annual average regeneration to be used for estimating processing expenses =

$$\frac{12,000 \text{ lb/day} \times 67 \text{ regeneration operation days}}{365 \text{ days/yr}} = 2203 \text{ lb/day}$$

The direct capital cost for fluid-bed regeneration from Figure 2-48 = 1,100 K\$ at a design rate of 14,040 lb/day. Processing expenses from Figure 4-29 = 43 K\$/yr. at an annual operating rate of 2203 lb/day.

Fresh Carbon Storage and Transfer

No fresh carbon storage is used. Fresh carbon is brought in by truck when required.

Spent Carbon Storage and Transfer

The spent carbon storage volume was specified as 855 ft³.

The direct capital cost for stainless steel spent carbon storage and transfer equipment from Figure 4-2 = 65 K\$. As with fresh carbon storage and transfer, processing expenses depend on how much carbon is transferred. This quantity corresponds to the average regeneration rate of 1808 lb/day. Processing expenses from Figure 4-3 = 4 K\$/yr.

Regenerated Carbon Storage and Transfer

The regenerated carbon storage volume is equal to the spent carbon storage volume of 855 ft³.

The direct capital cost for regenerated carbon storage and transfer from Figure 4-2 = 65 K\$. Processing expenses on the same basis as for spent carbon storage from Figure 4-3 = 4 K\$/yr.

Influent Pumping

The system design flow rate is 4 mgd. The design head requirement is 126 ft.

The direct capital cost for influent pumping from Figure 4-37 = 125 K\$. Processing expenses from Figure 4-38 = 48 K\$/yr based on an operating head of 100 ft.

Buildings and Site Preparation

Costs for buildings and for site preparation in Section 4 were based on standard design concepts defined there. Use of these costs requires an estimate of the areas for each. The area for buildings depends on how much of the GAC system is housed, and what additional requirements there are for offices, laboratories, and other facilities. Site preparation costs depend on total area including unhoused portions of the site.

Area estimates for computing both buildings and site preparation costs are obtained from estimates of process area. Area requirements for various process modules were provided in Figure 4-40 through 4-45.

For this case, the results are:

<u>Process Module</u>	<u>Area (ft)²</u>
Influent pumping	1500
Fresh carbon storage	-
Spent carbon storage	230
Regenerated carbon storage	230
Adsorbers	1600
Backwash	590
Regeneration	<u>1800</u>
Total Process area required	5950

This area is used to calculate costs for site preparation. From Figure 4-46, the direct capital cost = 10 K\$.

For the Cincinnati system, the buildings housed the entire installation except for the influent pumps. The estimated building area without the 25 percent additional area assumed in the examples in this report would therefore be 4450 ft². This compares with an actual building area of 4357 ft². The 25 percent adjustment used in other examples was intended as a contingency allowance for additional laboratory and office space. These areas were minimal in the Cincinnati project. For this estimate the building area of 4357 ft² is used.

From Figure 4-47, the direct capital cost = 170 K\$.

Building annual operating expenses include the costs of energy for lighting, heating, ventilating, air conditioning, and maintenance costs.

Energy costs depend on building area, geographical location, and energy prices. Table 4-7 lists energy requirements for a number of major metropolitan areas. Using the St. Louis, Missouri, location as an approximation to Cincinnati for this example, the energy expenses for the building are:

$$4357 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr} \times \$0.04/\text{kWh} = 24 \text{ K\$/yr.}$$

Assume annual maintenance expenses at 3 percent of direct capital cost. Maintenance expenses are:

$$.03 \times 170 \text{ K\$} = 5.1 \text{ K\$/yr.}$$

$$\text{Building annual operating expenses} = 29 \text{ K\$/yr.}$$

Carbon Losses

Carbon losses reported for this system are 11 percent of the carbon regenerated.

Carbon losses = $.15 \times 2203 \text{ lb/day} \times 365 \text{ day/yr} = 120,450 \text{ lb/yr}$.

Processing expense for carbon losses = $\$.50/\text{lb} \times 120,450 = 60.2 \text{ K\$/yr}$.

Interconnecting and Offsite Piping

Pipe sizes, lengths of lines, and valving needs must be estimated. Pipe sizes can be obtained from the flow rate and corresponding line sizes listed in Table 4-5.

Influent and effluent lines:

$$\frac{4 \times 10^6 \text{ gal/day}}{1440 \text{ min/day}} = 2.778 \text{ gpm}$$

The line size from Table 4-5 = 14 inches. Actual plant used 16 inches.

Carbon slurry lines:

Carbon slurry lines are based on a standard transfer rate in the range of 125 to 250 gpm of slurry. The line size from Table 4-5 = 4 inches.

Backwash lines (in and out):

Backwash lines depend on the adsorber size and backwash rate. At 10 gpm/ft² for an 11 ft diameter adsorber:

$$95 \text{ ft}^2 \times 10 \text{ gpm/ft}^2 = 950 \text{ gpm}.$$

The line size from Table 4-5 = 10 inches. The size actually used in the Cincinnati plant was 10 inches.

Surface wash lines:

None used in this example.

Service lines for compressed air and plant water:

Assume 2" lines for services to the process area. These lines will supply natural gas, fuel oil, compressed air, and plant water.

Detailed information on the lengths of these lines was not available. Lengths were assumed. Direct capital costs for piping are obtained from Table 4-1. The number of valves must also be specified. Here it is assumed that two valves are required in each line. Costs for valves are obtained from Table 4-2.

A summary for interconnecting and offsite piping is given below:

<u>Line</u>	<u>Size (in)</u>	<u>Length (ft)</u>	<u>Direct Capital Cost (K\$)</u>	
			<u>Piping</u>	<u>Valves</u>
Influent	14	225	10.7	9.4
Effluent	14	225	10.7	9.4
Carbon slurry lines	4	225	2.8	1.3
Backwash in	10	225	7.2	4.8
Backwash out	10	225	7.2	4.8
Services	2	500	<u>1.4</u>	<u>0.9</u>
			40.0	+ 30.6 = 70.6 K\$

Annual maintenance expenses at 1 percent per year = 0.7 K\$/yr.

Electrical Supply and Distribution

An estimate of the total installed electrical requirement is obtained by summing the major power requirement for power consuming modules. An allowance of 20 percent over this volume is provided as a design contingency. Major system power requirements are for influent pumping, backwash pumping, carbon slurry transfers, regeneration, and building needs.

Power needs for each module are as follows:

Power is for pumping influent water to the adsorbers.

Power = 0.52 x flow rate in mgd . pumping head in psig

In this case, Power = 0.52 x 4 x 34 = 71 kW

Carbon storage and transfer:

Power needs are for pumping carbon slurries during various transfer operations between the adsorbers and storage vessels. Power needs between carbon storage and regeneration are included under regeneration power requirements.

The power required for carbon slurry transfer depends on whether an eductor or direct pump system is used for transfer, with the slurry concentration, with the rate at which the slurry is pumped, and the pumping head. Power for the eductor is supplied to the motive water pump. In direct pump systems, power is supplied directly to the slurry pumps themselves.

In this report, the basis for slurry transfer power needs is a fixed transfer rate of 70 gpm of slurry.

For an eductor system, the motive water required is 5 times the process stream rate for a total of 350 gpm. The motive water must be supplied at a head pressure 60 psig above the eductor discharge pressure. For a discharge of 32 psig used in this example, the motive water supply pump head pressure is 92 psig.

Pumping Power = $.00075 \times \text{flow rate in gpm} \times \text{pumping head in psig}$.

Eductor power is therefore:

$$\text{Power} = .00075 \times 350 \times 92 = 24 \text{ kW}$$

For a direct pump system, the power at a discharge of 32 psig is:

$$\text{Power} = .00075 \times 70 \times 32 = 1.7 \text{ kW}.$$

Since it is unlikely that the intermittent carbon transfers between adsorbers and storage will occur simultaneously, the installed power requirements calculated above are sufficient, even though three separate types of storage are involved.

Backwash

Power for the backwash system depends on the pumping rate and pumping head requirement. The pumping rate depends on individual adsorber area and the backwash flow rate per unit adsorber area. Pumping head depends on overall system design. In this report, backwash costs are based on a backwash flow rate per unit adsorber area of 18 gpm/ft^2 and an assumed pumping head requirement of 22 psig.

$$\text{Power} = .00075 \times 18 \times 22 \times \text{individual adsorber area in ft}^2.$$

In this case, the individual adsorber area is 113 ft^2 .

$$\text{Power} = .00075 \times 18 \times 22 \times 113 = 34 \text{ kW}$$

Regeneration

Power required for regeneration depends on regeneration rate.

Requirements for the fluid bed are:

$$\text{Fluid bed power requirement} = .05 \text{ kWh/lb} \times 14,040 \text{ lb/day} = 702 \text{ kW}$$

Buildings

The power required for buildings depends on size, location, and specific needs for heating, lighting, ventilation, and air conditioning. Average needs were given in Table 4-7.

In this case, the building area is 4357 ft². A single-story building is specified. Assuming a St. Louis, MO location to simulate the Cincinnati location, the power requirement is:

$$\text{Power} = \frac{4357 \text{ ft}^2 \times 138.7 \text{ kWh/ft}^2/\text{yr}}{8760 \text{ hr/yr}} = 69 \text{ kW}$$

Total Installed Power Requirement

Adding the above and applying a factor of 1.2, the total is:

$$900 \text{ kW} \times 1.2 = 1080 \text{ kW}$$

The direct capital cost for an electrical substation and distribution system from Figure 4-39 = 40 K\$.

Annual maintenance expenses at 2 percent of direct capital cost = 0.8 K\$/yr.

APPENDIX F
GAC MODULE COST EQUATIONS

TABLE F-1. GAC MODULE COST EQUATIONS^a

Nomenclature:		Equation	
A = area in square feet (ft ²)			
C = cost in thousands of dollars (direct capital cost) or thousands of dollars per year (processing expenses)			
D = diameter feet (ft)			
R = regeneration rate, pounds per day (lb/d)			
P = installed electric power capacity, in kilowatts (kW)			
V = volume in cubic feet (ft ³)			
W = weight of carbon, pounds (lb)			
e = natural logarithm base e.			
Process Module			
Carbon storage and transfer - direct capital cost			
stainless steel		C = .195 V ^{.533}	
carbon steel		C = .122 V ^{.518}	
Carbon storage and transfer - processing expenses			
carbon transfer rate 50,000 lb/d		C = 20.08 V ^{.015}	
20,000 lb/d		C = 5.914 V ^{.0671}	
10,000 lb/d		C = 1.786 V ^{.145}	
5,000 lb/d		C = .660 V ^{.209}	
2,000 lb/d		C = .164 V ^{.331}	
1,000 lb/d		C = .0532 V ^{.443}	
500 lb/d		C = 0.372 V ^{.471}	
<500 lb/d		C = .0275 V ^{.505}	
Concrete adsorber - direct capital cost			
complex construction		C = 69.5 + .0043 V	
simple construction		C = 6.245 V ^{.306}	
Concrete adsorber - processing expenses			
total		C = 8.73 + 0.0128 A - 4.83 x 10 ⁻⁷ A ²	
Gravity steel adsorber - direct capital cost			
30 ft diameter		C = 126.4 + .0694 V	
20 ft diameter		C = 62.14 + .0929 V	

(Continued)

TABLE F-1. GAC MODULE COST EQUATIONS (Continued)

Gravity steel adsorber - processing expenses	
30 ft diameter - total	$C = 20.9 + .0170 A$
20 ft diameter - total	$C = 22.4 + .00925 A$
Pressure steel adsorber - direct capital cost	
12 ft with backwash	$C = 90 + .02 V$
8, 10 ft with backwash	$C = 66.9 + .0228 V$
12 ft without backwash	$C = 46.3 + .0234 V$
8, 10 ft without backwash	$C = 38.04 + .0245 V$
Pressure steel adsorbers - processing expenses	
total	$C = 21.9 + .0246 A$
Packaged adsorber systems - direct capital cost	$C = 2.02 A^{.528}$
Packaged adsorber systems - processing expenses	$C = 1.25 + 0.0114A - 5.91 \times 10^{-6} A^2$
Pulsed bed adsorber - direct capital cost	
12 ft	$C = 62.1 + 0.0261 V$
10 ft	$C = 0.315 V^{.732}$
8 ft	$C = 1/(0.0184 - 3.64 V)$
Pulsed bed adsorber - processing expenses	
total	$C = 20.6 + .0262 A$
Backwash module - direct capital cost	
pumps and storage	$C = 2.205 A^{.651}$
pumps only	$C = 2.72 A^{.665}$
Backwash module - processing expenses	
20 adsorber vessels	$C = 4.15 + .057 A$
10 adsorber vessels	$C = 3.69 + .0319 A$
5 adsorber vessels	$C = 3.55 + .019 A$
2 adsorber vessels	$C = 3.22 + .0096 A$
1 adsorber vessel	$C = A/(38.1 + .0717 A)$

(Continued)

TABLE F-1. GAC MODULE COST EQUATIONS (Continued)

Surface wash module - direct capital cost	
20 adsorber vessels	$C = 22.2 + .873 A$
10 adsorber vessels	$C = .548 A$
5 adsorber vessels	$C = A/(4.26 + .00384 A)$
2 adsorber vessels	$C = A/(5.77 + .00775 A)$
1 adsorber vessel	$C = .557 A$
Surface wash module - processing expenses	
20 adsorber vessels	$C = 1.63 A$
10 adsorber vessels	$C = 1.57 A$
5 adsorber vessels	$C = 1.30 A$
2 adsorber vessels	$C = 1.16 A$
1 adsorber vessel	$C = 1.35 A$
Air scour module - direct capital cost	
10 ft. hydraulic head	$C = 1.14 A$
20 ft. hydraulic head	$C = 1.62 A$
40 ft. hydraulic head	$C = 2.28 A$
Air scour module - processing expenses	
10 ft. hydraulic head	$C = .600 + .033A + 2.5 \times 10^{-5} A^2$
20 ft. hydraulic head	$C = .208 + 0.827A - 1.78 \times 10^{-5} A^2$
40 ft. hydraulic head	$C = .797 + .150A - 2.66 \times 10^{-6} A^2$
Initial carbon charge - direct capital cost	$C = .00075 W$
Multihearth regeneration furnace - direct capital cost	$C = 383 + .0369 R$
Multihearth regeneration furnace - processing expenses total	$C = 31.8 + .0112 R$
Fluid-bed regeneration furnace - direct capital cost	$C = 771 + .0214 R$
Fluid-bed regeneration furnace - processing expenses total	$C = 57 e$
	$5.4 \times 10^{-5} R$
Infrared regeneration furnace - direct capital cost	$C = 217 + .0230 R$
Infrared regeneration furnace - processing expenses total	$C = 43 + .032 R$

(Continued)

TABLE F-1. GAC MODULE COST EQUATIONS (Continued)

Off-site regeneration - processing expenses	
distance to regeneration facility 100 miles	$C = 348 + .0201 R$
25 miles	$C = 199 + .01 R$
10 miles	$C = 109 + .00578 R$
Influent pump station - direct capital cost	
pumping head, 100 ft	$C = 62 + 14.6 R$
80 ft	$C = 55.1 + 11.0 R$
40 ft	$C = 43.6 + 9.19 R$
Influent pump station - processing expenses	
pumping head, 100 ft	$C = 8.06 + 9.85 R$
80 ft	$C = 2.16 + 8.93 R$
40 ft	$C = 7.60 + 3.66 R$
Electrical supply and distribution	
- direct capital cost	$C = 0.00947P + 5.31$
Site preparation - direct capital cost	$C = 4.33 \times 10^{-4} A + 0.682$
Buildings - direct capital cost	
floor area	$C = 0.0371 A - 0.7071$

^aThese equations were obtained by curve fitting three or more individual cost/capacity data sets for each module. The equations were selected based on a best fit of the data and therefore are approximate (within 10-15 percent) for any given cost/capacity data set.

APPENDIX G

CONVERSION OF AMERICAN TO INTERNATIONAL SYSTEM (SI)* UNITS

APPENDIX G

CONVERSION OF AMERICAN TO INTERNATIONAL SYSTEM (SI)* UNITS

LENGTH	ft	meters	0.305
AREA	ft ²	meters ²	0.0929
	acres	meters ²	4047
VOLUME	ft ³	meters ³	0.0283
	gallons	meters ³	0.00379
MASS	lb	kilograms	0.454
	tons	megagrams	0.907
WEIGHT RATE OF FLOW 10 ³	lb/hr	kg/sec	0.126
	tons/day	kg/sec	0.0105
VOL. RATE OF FLOW	gallons/min	meters ³ /sec	6.309 x 10 ⁻⁶
	gallons/min	millimeters ³ /sec	6309
ENERGY	Btu	kilojoule (=Newton x meter)	1.055
	kw-hrs	megajoules	3.60
POWER	H.P.	Joules/sec	746
	kw	Joules/sec	1000
	10 ⁶ Btu/hr	kilojoules/sec	293
PRESSURE	lb/in ²	kilopascal	6.895
		(= kilonewton/m ²)	
TEMPERATURE	°F	°K	0.556
			(°F + 459.7)

* Standard for Metric Practice, American Society for Testing and Materials, E380-76, 1976.

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